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SUMMARY TECHNICAL REPORT
OF THE
NATIONAL DEFENSE RESEARCH COMMITTEE

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[redacted]

Manuscript and illustrations for this volume were prepared for publication by the Summary Reports Group of the Columbia University Division of War Research under contract OEMsr-1131 with the Office of Scientific Research and Development. This volume was printed and bound by the Columbia University Press.

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SUMMARY TECHNICAL REPORT OF DIVISION 14, NDRC

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VOLUME 2

MILITARY AIRBORNE RADAR SYSTEMS
< [MARS] >

OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT
VANNEVAR BUSH, DIRECTOR

NATIONAL DEFENSE RESEARCH COMMITTEE
JAMES B. CONANT, CHAIRMAN

DIVISION 14
A. L. LOOMIS, CHIEF

WASHINGTON, D. C., 1946

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NOTES ON THE ORGANIZATION OF NDRC

The duties of the National Defense Research Committee were (1) to recommend to the Director of OSRD suitable projects and research programs on the instrumentalities of warfare, together with contract facilities for carrying out these projects and programs, and (2) to administer the technical and scientific work of the contracts. More specifically, NDRC functioned by initiating research projects on requests from the Army or the Navy, or on requests from an allied government transmitted through the Liaison Office of OSRD, or on its own considered initiative as a result of the experience of its members. Proposals prepared by the Division, Panel, or Committee for research contracts for performance of the work involved in such projects were first reviewed by NDRC, and if approved, recommended to the Director of OSRD. Upon approval of a proposal by the Director, a contract permitting maximum flexibility of scientific effort was arranged. The business aspects of the contract, including such matters as materials, clearances, vouchers, patents, priorities, legal matters, and administration of patent matters were handled by the Executive Secretary of OSRD.

Originally NDRC administered its work through five divisions, each headed by one of the NDRC members. These were:

Division A — Armor and Ordnance
Division B — Bombs, Fuels, Gases, & Chemical Problems
Division C — Communication and Transportation
Division D — Detection, Controls, and Instruments
Division E — Patents and Inventions

In a reorganization in the fall of 1942, twenty-three administrative divisions, panels, or committees were created, each with a chief selected on the basis of his outstanding work in the particular field. The NDRC members then became a reviewing and advisory group to the Director of OSRD. The final organization was as follows:

Division 1 — Ballistic Research
Division 2 — Effects of Impact and Explosion
Division 3 — Rocket Ordnance
Division 4 — Ordnance Accessories
Division 5 — New Missiles
Division 6 — Sub-Surface Warfare
Division 7 — Fire Control
Division 8 — Explosives
Division 9 — Chemistry
Division 10 — Absorbents and Aerosols
Division 11 — Chemical Engineering
Division 12 — Transportation
Division 13 — Electrical Communication
Division 14 — Radar
Division 15 — Radio Coordination
Division 16 — Optics and Camouflage
Division 17 — Physics
Division 18 — War Metallurgy
Division 19 — Miscellaneous
Applied Mathematics Panel
Applied Psychology Panel
Committee on Propagation
Tropical Deterioration Administrative Committee

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NDRC FOREWORD

As events of the years preceding 1940 revealed more and more clearly the seriousness of the world situation, many scientists in this country came to realize the need of organizing scientific research for service in a national emergency. Recommendations which they made to the White House were given careful and sympathetic attention, and as a result the National Defense Research Committee [NDRC] was formed by Executive Order of the President in the summer of 1940. The members of NDRC, appointed by the President, were instructed to supplement the work of the Army and the Navy in the development of the instrumentalities of war. A year later, upon the establishment of the Office of Scientific Research and Development [OSRD], NDRC became one of its units.

The Summary Technical Report of NDRC is a conscientious effort on the part of NDRC to summarize and evaluate its work and to present it in a useful and permanent form. It comprises some seventy volumes broken into groups corresponding to the NDRC Divisions, Panels, and Committees.

The Summary Technical Report of each Division, Panel, or Committee is an integral survey of the work of that group. The first volume of each group's report contains a summary of the report, stating the problems presented and the philosophy of attacking them, and summarizing the results of the research, development, and training activities undertaken. Some volumes may be "state of the art" treatises covering subjects to which various research groups have contributed information. Others may contain descriptions of devices developed in the laboratories. A master index of all these divisional, panel, and committee reports which together constitute the Summary Technical Report of NDRC is contained in a separate volume, which also includes the index of a microfilm record of pertinent technical laboratory reports and reference material.

Some of the NDRC-sponsored researches which have been declassified by the end of 1945 were of sufficient popular interest that it was found desirable to report them in the form of monographs, such as the series on radar by Division 14 and the monograph on sampling inspection by the Applied Mathematics Panel. Since the material treated in them is not duplicated in the Summary Technical Report of NDRC, the monographs are an important part of the story of these aspects of NDRC research.

In contrast to the information on radar, which is of widespread interest and much of which is released to the public, the research on subsurface warfare is largely classified and is of general interest to a more restricted group. As a consequence, the report of Division 6 is found almost entirely in its Summary Technical Report, which runs to over twenty volumes. The extent of the work of a Division cannot therefore be judged solely by the number of volumes devoted to it in the Summary Technical Report of NDRC: account must be taken of the monographs and available reports published elsewhere.

To A. L. Loomis, Chief of Division 14, the men who worked under his direction, and the personnel of the Division's contractors belongs major credit for the perfection of a device which forcefully altered the course of the war. The application of radar by all Services in all theaters of operation is an eloquent testimonial not only to the skill of these men but also to their will, their loyal cooperation, and their scientific integrity. The Summary Technical Report of the Division, prepared under the direction of the Division Chief and authorized by him for publication, therefore not only describes a major portion of their technical activities but is also a record of able American scientists and engineers cooperating fully in the defense of their country.

It is assuring to know that their contributions in the new field of microwaves will not be placed in intellectual cold storage to await purely military applications, but instead will soon find use in the industry, the transportation, the communications, and the scientific researches of a peacetime world.

For their work in opening a broad entrance to a new field of knowledge as well as for their invaluable contributions in a time of desperate strife, we join the Nation in expressing our sincere appreciation.

Vannevar Bush, Director
Office of Scientific Research and Development

J. B. Conant, Chairman
National Defense Research Committee

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FOREWORD

The first of the three projects initiated by the Microwave Section of the National Defense Research Committee in the summer of 1940 was the development of *aircraft interception radar* [AI] to permit successful attack of bombers by fighter planes at night or in overcast. Throughout World War II the development of radar equipment for military and naval aircraft was the major activity of Division 14. In addition to the laboratory development of radar equipment, Division 14 was directly concerned with the several other steps necessary for the introduction of new equipment to Service use, including experimental trial, engineering, consultation in the production on Service contract, acceptance and operational tests, installation as well as maintenance, modification, and other aspects of field service. It is logical, therefore, that in the Summary Technical Report of the Division program, one complete volume should be devoted to airborne radar.

The Division 14 Summary Technical Report consists of three volumes of which *MARS* is the second. The first volume, *Radar*, contains a summary of the Division 14 and Radiation Laboratory activities and special project reports. It will serve as a general guide to the Division projects and activities. The third volume is a complete bibliography of Division 14 and Radiation Laboratory reports listed by serial number, subject, organization, and in the case of Radiation Laboratory reports, by author.

The largest publication effort of Division 14 is the Radiation Laboratory Series published by the McGraw Hill Book Company, which is included as a supplement to the Summary Technical Report. This series consists of some twenty-eight volumes and an index. It is a complete report on the state of the radar art at the end of World War II, including texts on fundamental electronics, component and system design and engineering, peacetime applications, and Loran navigation.

A brief review of all the component and systems projects undertaken within Division 14 is given in the Final Project Report dated December 1945. The history of Division 14 and the Radiation Laboratory is told in the book *Radar*, published by Little, Brown & Company as a part of the Long History of OSRD.

The *MARS* volume was prepared for Division 14 by the Massachusetts Institute of Technology Radiation Laboratory. The Radiation Laboratory as the principal contract of Division 14 accounted for over 75 per cent of the Division's dollar appropriations to contracts and participated in every phase of the Division program.

MARS may therefore quite naturally emphasize Radiation Laboratory airborne radar developments, its policies, and its opinions. It is not, however, limited to a discussion of Radiation Laboratory activities. Wherever desirable for a complete treatment of the subject, use has been made of material from the industrial concerns which participated in the development and production of the equipments on Army and Navy as well as on OSRD contracts. Also included is material received from Service laboratories, testing agencies, and operational groups, including principally the results of their experience in the planning, development, and introduction of new equipment. It has not been possible in most cases to make direct reference to the sources of material. The assistance of these many organizations which took part in the wartime radar program and contributed directly or indirectly to the preparation of this book is gratefully acknowledged. Specific acknowledgment is due to Bell Telephone Laboratories, Inc., General Electric Company, Galvin Manufacturing Corporation, Philco Corporation, Lukas Harold Company, and Radio Corporation of America.

MARS was written by members of the Airborne Division of the Radiation Laboratory with an Editorial Board consisting of F. R. Banks, J. J. Hibbert, L. J. Laslett, E. M. Lyman, Sims McGrath, R. M. Robertson, R. M. Thrall, and R. B. Whitney. Dr. Thrall was editor of *MARS*. He succeeded Dr. Laslett who as the first editor was responsible for the early planning and organization. It should be noted that the volume was written, after a short planning period, in less than four months. At this speed there was not sufficient time to permit all of the editing desirable. The individual authors of the various chapters were permitted complete freedom of opinion on controversial subjects such as the selection of equipment for future requirements as well as the most effective methods of test, introduction, and use.

A. L. Loomis
Chief, Division 14

L. A. DuBridge
Director, Radiation Laboratory

TITLES OF DIVISION 14 SUMMARY TECHNICAL REPORTS

SUMMARY TECHNICAL REPORT OF DIVISION 14, NDRC

Volume 1 Radar: Summary Reports and Harp Project

Volume 2 Military Airborne Radar Systems (MARS)

Volume 3 Bibliography of Division 14 and Radiation Laboratory Reports

RADIATION LABORATORY SERIES

(Published by the McGraw-Hill Book Company)

1. Radar System Engineering, Louis N. Ridenour
2. Radar Aids to Navigation, J. S. Hall
3. Radar Beacons, A. Roberts
4. Loran, J. A. Pierce, A. A. McKenzie, R. H. Woodward
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24. Threshold Signals, J. L. Lawson, G. E. Uhlenbeck
25. Theory of Servomechanisms, H. M. James, N. B. Nichols, R. S. Phillips
26. Radar Scanners and Radomes, W. M. Cady, M. B. Karelitz, L. A. Turner
27. Computing Mechanisms and Linkages, A. Svoboda
28. Index

PREFACE

The primary purpose in writing the book, *Military Airborne Radar Systems* [*MARS*], was to put in permanent form a description of the status of radar for military use in airplanes, at the close of World War II. The book *MARS* consists of 24 chapters of which the first is general and the remaining 23 are divided into five parts. These parts represent a subdivision of military airborne radar systems into classes according to function.

Part I treats *aircraft-to-surface vessel* [ASV] radars. ASV comes first partly because of its historical position among radar systems but primarily because of the relative simplicity of the ASV systems. It is hoped that this simplicity will give the reader who is unfamiliar with radar systems an easy approach to the subject. The titles of the four chapters that comprise Part I indicate the major considerations which apply to all radar systems. These considerations are: (1) function of the system, namely, what the system is to be used for; (2) the theoretical basis for and general features of the system; (3) what things must be kept in mind in the actual design of the system once its general features have been decided; (4) how the system can be made to work and kept working and how well it does work.

Part II treats radar bombing. The opening chapter, Chapter 6, contains a summary of the part and a brief introduction to the geometric problem of bombing including a partial description of the theory and operation of the Norden bombsight. Chapter 7 treats the airborne radar systems used for bombing. Chapters 8 and 9 treat bombing computers to be used with these airborne radar systems. Not all bombing computers are discussed but enough are treated to give a fair picture of the state of the art at the close of World War II. Chapters 10 and 11 discuss ground-aided bombing — beacon bombing in Chapter 10 and close-support bombing in Chapter 11. Chapter 12 treats toss bombing, a type of bombing used by fighter planes and light bombers. Problems of toss bombing are almost completely unrelated to those of the other kinds of bombing treated in the earlier chapters, being more closely related to the problems of fire control (see Part IV). Chapter 13 treats problems of assessment and training incidental to the successful use of radar for bombing.

Part III treats *aircraft interception* [AI]. Chapter 14 introduces the problem; Chapter 15 discusses the equipments used; and Chapter 16 deals with AI tactics.

Part IV treats airborne radar systems used for fire control. Chapter 17 is introductory in nature and emphasizes some of the problems encountered in the development of airborne radar fire-control systems. Chapter 18, "Automatic Following Equipment," treats the most complicated of the fire-control systems. Chapter 19 treats a somewhat less complicated (nonautomatic) type of equipment. Chapter 20 treats radar systems used for range-to-target only. This includes systems suitable for ranging from one aircraft to another aircraft, systems suitable for ranging from an aircraft to a ground target, and systems which will do both. Chapter 21 treats computers (gunsights) to accompany the radar systems. Since very little of the computer work was done at the Radiation Laboratory [RL] there is very little discussion of specific computers in Chapter 21. The orientation of the chapter is toward the problems of combining radar systems and computing systems into overall fire-control systems. (Other volumes of the STR give quite satisfactory coverage and descriptions of specific computers. See the bibliography of Part IV.) Chapter 22 discusses the problems of assessing fire-control radar systems and is based on experiences of RL personnel, both at Service testing agencies and at the Radiation Laboratory.

Part V, *airborne moving target indication* [AMTI], treats a series of developments which came at the very end of the war. These systems show considerable military promise, but the treatment of them in the present volume is confined primarily to the technical details of the system.

The foregoing description of the various parts of book *MARS* does not give a complete picture of the purpose of the volume. We accordingly supplement the above part-by-part description with a discussion of the several theses of the volume and the places where these are treated. The basic purpose of the book *MARS*, as the general title Summary Technical Report implies, is to give a description of the status of airborne radar at the close of World War II. Realizing that the rapid rate of development of radar systems will make most of the systems in use during the war obsolete (in some cases even by the time this book is released) only a minimum number of systems have been described in detail. The reader is referred to the bibliography for detailed technical descriptions. The chapters which are primarily concerned with description of radar systems are 3, 4, 5, 7, 15, 18, 19, 20, 23, and 24.

In many cases effective use of a radar system requires auxiliary computers. Given a radar system and a computer to go with it, it is then necessary to study the tactical importance of the combination. Discussions of tactics and computers come in Chapter 2 for ASV and in Chapters 8, 9, 10, 11, and 12 for bombing, in Chapters 14 and 16 for AI, and in Chapter 21 for fire control.

After a radar system and the appropriate attachments have been developed it becomes important to consider how the combination will function. It may be that several systems all designed for the same general function are offered to the Armed Services at approximately the same time. It is then necessary for the military testing agencies to conduct comparative performance tests so as to decide which of the competing systems should be developed. The importance of assessment is emphasized in Chapter 1; Chapter 22 gives a picture of the assessment situation for fire-control systems. In addition to assessing the systems, there is the major problem of assessing performance of military personnel being trained to use the equipment; this is discussed in Chapter 13, which also treats the general importance of an effective training program not only for operators but for maintenance men and staff officers as well. The problem of maintenance of radar systems as it concerns test equipment needed and procedures to be followed is discussed first (and in most detail) in Chapter 5 for ASV. Certain modifications for the more complicated radar systems are considered in Chapter 7 for bombing and Chapter 15 for AI.

Few of the staff members of the Radiation Laboratory realized when they entered the field of military research how long a road must be traversed in order to successfully introduce a new piece of equipment into military use. The initial thought of many a scientist was that a sufficient contribution would be to supply a laboratory model of the proposed new equipment. He realized that he might have to show the equipment to a representative of the Armed Services and later, perhaps, spend a few weeks with the engineer and the manufacturer for the equipment. In contrast to this early expectation, it was soon learned that the man who designed the equipment should follow it closely every step of the way. This includes, first, demonstrating the merits of the equipment to the Armed Services, which usually entails close cooperation with the military testing agencies; next, the designer must keep in close touch with the manufacturer and the Armed Services throughout the whole preproduction stage; he should follow his equipment into the training stages and then finally to the combat theater. The extent of participation by Radiation Laboratory personnel in these various phases is indicated in the summary report of Dr. L. A. DuBridge (see Volume 1 of the Division 14 STR). The chapters of the book *MARS* which treat the general position of the scientist in warfare and related problems are 1, 13, 17, 21, and 22.

The reader's attention is called to the presence of the bibliography, glossary, and index at the end of the book. The arrangement of the bibliography and the notation for references are discussed at the beginning of the bibliography.

The table of contents indicates the author (or authors) of each section of the book. I wish to express my appreciation to all of the authors; to the members of the *MARS* editorial board, and especially to Dr. R. B. Whitney, who served as Associate Editor during the latter months of the preparation of this volume; and to the *MARS* production staff: Emily Blech, Doris Burton, Ann Klein, Jean McBeath, Pagonia Poulos, Jennie Scarponi, Bernice Zamett, for their cooperation and loyalty in the various stages of publication.

Finally, Division 14 wishes to state its appreciation to the U. S. Army and to the following organizations for permitting the use of their material in the illustration of this volume: Bell Telephone Laboratories, Galvin Manufacturing Corporation, General Electric Company, and the Sperry Gyroscope Company. The source of the figures is the Radiation Laboratory unless otherwise noted.

R. M. Thrall
Editor

This volume, like the seventy others of the Summary Technical Report of NDRC, has been written, edited, and printed under great pressure. Inevitably there are errors which have slipped past Division readers and proofreaders. There may be errors of fact not known at time of printing. The author has not been able to follow through his writing to the final page proof.

Please report errors to:

JOINT RESEARCH AND DEVELOPMENT BOARD
PROGRAMS DIVISION (STR ERRATA)
WASHINGTON 25, D. C.

A master errata sheet will be compiled from these reports and sent to recipients of the volume. Your help will make this book more useful to other readers and will be of great value in preparing any revisions.

CONTENTS

CHAPTER PAGE

1 Scientists in Warfare by *M. G. White* 1

PART I
RADAR MEANS FOR DETECTION OF SURFACE VESSELS FROM AIRCRAFT
By S. McGrath 7

2 Functions of ASV Radars by *G. A. Garrett* 9
3 Means of ASV Detection by *G. A. Garrett, S. McGrath* . . 13
4 Design Considerations by *G. A. Garrett, S. McGrath* . . 17
5 ASV Performance by *S. McGrath, A. D. Cole, G. R. Banks* 25

PART II
RADAR BOMBING
By J. J. Hibbert 35

6 The Bombing Problem by *W. J. Tull, S. McGrath* . . . 37
7 Airborne Radar Systems for Bombing by *J. J. Hibbert, D. Halliday, D. L. Hagler, F. R. Banks* 47
8 Bombing Computers for Radar Mapping Systems by *W. J. Tull, D. L. Hagler, E. A. Luebke, J. J. Hibbert, W. Deerhake, S. McGrath* 66
9 The GPI Bombing and Navigation Computer by *W. J. Tull, N. W. MacLean* 87
10 Beacon Bombing by *J. B. Platt, R. B. Lawrance* 104
11 Ground-Controlled Bombing by *E. Lyman, G. D. Huff* . 131
12 Application of Radar to Toss Bombing by *L. J. Laslett* . 139
13 Radar Bombing Assessment and Training by *J. J. Hibbert, G. E. Wheeler, J. E. Ward, T. A. Murrell, E. A. Luebke, V. Holdam, J. H. Buck, E. M. Lyman* 155

PART III
AIRCRAFT INTERCEPTION

PAGE

By R. McG. Robertson 173

CHAPTER

14 The Interception of Enemy Aircraft by *R. McG. Robertson* 175
15 AI Equipment by *W. M. Cady, F. R. Banks* 178
16 Aircraft Interception Tactics by *F. R. Banks, T. W. Bonner* 188

PART IV
AIRBORNE FIRE-CONTROL RADAR

By R. B. Whitney 195

17 General Considerations on Airborne Fire Control by *R. M. Thrall, R. B. Whitney* 197
18 Automatic Following Equipment by *H. G. Brewer* . . . 200
19 Manually Directed Radar Gunsights by *V. Holdam* . . 219
20 Combined Optical and Radar Fire Control by *E. H. B. Bartelink* 226
21 Computer Problems by *R. M. Thrall* 248
22 Assessment Problems by *R. B. Whitney* 256

PART V
AIRBORNE MOVING TARGET INDICATORS

By E. M. Lyman 277

23 Basic Principles of AMTI by *E. M. Lyman* 279
24 Airborne Moving Target Indicator Systems by *E. M. Lyman* 287
Glossary 303
Bibliography 309
OSRD Appointees 320
Index 321

Chapter 1

SCIENTISTS IN WARFARE

1.1 GENERAL PURPOSE OF BOOK

This book on military applications of airborne radar systems is presented by members of the Airborne Division of the Radiation Laboratory with the hope that it will prove interesting and stimulating to those who take up our work as we disband. Our point of view in writing about radar systems is quite different from that adopted in the Radiation Laboratory Technical Series.[a] Where the latter series discusses technical design in detail and is intended to lay bare the scientific framework of radar, this volume treats the subjects from the overall operational point of view. If one compares the Technical Series to reports on medical laboratory research it would be appropriate to classify this present volume as a clinical study of the "patient-as-a-whole." Throughout this presentation we emphasize the tactical requirements, the military problem, the reaction of the operators and, generally speaking, all those diverse human elements that only experience uncovers.

A book which deals in specific equipments runs the risk of becoming dated even before it reaches the public. The reader is urged to consider the following chapters as more than a mere history of airborne microwave radar from 1940 to 1945. They should be regarded as a study of the application of new scientific and technological developments to problems of warfare. Should war come again, some other powerful technical innovation may require the coordinated efforts of this country's scientists, engineers, and military personnel. It is to be hoped that lessons learned in this war will not pass unnoticed and that the fumbling in the dark days of 1940–1942 will not be repeated. The reader should therefore pay close attention to the tactical thinking, to the general approach to the military problem in order to gain insight into the factors which made possible the development of so many important radars. Although the equipments to be discussed may well be stepping stones to the future, we regard the scientific point of view which this book tries to convey as more important than details of equipment.

1.2 SCIENTISTS AND MILITARY PROBLEMS

Before turning to specific military problems, we may profitably discuss the general relation between scientists and military problems, for this relation almost completely controls the degree to which the scientist can contribute.

Even a casual study reveals that big advances in tactical thinking and technical warfare have come from sources but very loosely tied to the military agencies. By the very nature of a major advance it is impossible to predict or "whistle up" a revolutionary discovery. This holds for straight tactical, technical thinking as well as for basic science. It is necessary, therefore, to avoid excessive regimentation (often introduced in the guise of coordination or standardization) lest available national talent be too sharply directed into fields of short-range interest. For this and many other reasons it is best to rely upon civilian scientists in civilian institutions for the major technical and associated tactical advances. Obviously the detailed working out of tactical employment can only be done within the military structure, but even here World War II has demonstrated that civilian scientists belonging to civilian agencies must have the opportunity to introduce new equipment and even new tactical concepts at all levels of the military organization. Failure to recognize this function as legitimate has cost unnecessary delay, inefficient use, and even complete lack of appreciation of potentialities on the part of military agencies.

A book such as this is intended to be cannot present all the evidence in support of this thesis, but if any convincing is required, a comparison may be made between the wartime role of our American scientists and that of the German and Italian. Anglo-American science was essential to winning the war. Axis scientists were quickly surpassed by the victors, largely because the latter scientists were generally welcomed by the military at all levels even though they were associated with a separate organization in which they were free to work on new developments no matter how unpromising they appeared initially. There is little need to fear that free scientists, properly informed, will ignore the problems clamoring for attention; indeed there is more danger that they will be overly impressed by the current military problems and so fail to make revolutionary developments in advance of their need in battle.

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[a] A technical series of approximately thirty volumes has been prepared by the Radiation Laboratory staff for publication by the McGraw-Hill Book Co.

According to all information available to us the Axis' use of scientists was in sharp contrast to our policy. Second-rate scientists climbed into positions of authority and never gained the full confidence of the military, with the result that the scientists, being uninformed, indulged in many useless and fantastic enterprises. Exceptions, such as rocket development, do not alter the general belief that German scientists found little encouragement to consider themselves essential to the winning of the war. This was indeed most fortunate for us, as we now know after the events at Hiroshima and Nagasaki.

Axis scientists suffered either from over direction in government and industrial laboratories, or else had little contact with the military problem. True, the military agencies granted contracts to various institutional laboratories, but apparently very little of direct military interest was expected or delivered. This is in strong contrast with the way in which the Office of Scientific Research and Development organized and directed the work of American scientists.

1.3 THE SECURITY PROBLEM

As was pointed out, science in its military applications as well as in its basic form, must be a "free science" in order to be strong. If this is granted, several more steps should be taken by both military and scientific agencies. One has to do with the thorny question of secrecy. Contributing parties must be adequately informed about the tactical and technical problems. In spite of this obvious fact, there was far too much indiscriminate, blind classification of military information, scientific discoveries, technical equipment, and correspondence. Not only were our civilian scientists given too little access to military planning but they were also kept in mutual ignorance of scientific advances in cognate fields. Discoveries made in radar should have received much wider dissemination to those working in communications, television, underwater sound, and other fields. That these discoveries were not so distributed is a sad reflection on the scientists themselves who were temporarily forgetful of the very essence of creative thinking — freedom of publication. No one is suggesting unrestricted publication in the public journals, but surely there could have been a series of classified journals, available to *all* cleared scientists, which would have broken down artificial and highly injurious barriers. The writer has personal knowledge of many instances where greater restricted distribution of basic scientific and technological data would have profoundly increased our scientific strength.

With the coming of peace and talk about split-second pushbutton warfare of the future, we are faced with a most difficult problem in secrecy. In the midst of war it is clear that the best security lies in speed, in achievement, and not necessarily in secrecy. That secrecy can defeat its own purpose is shown by the frequency with which enemy scientists independently discovered techniques zealously guarded by us. Our secrecy merely slowed our own production and decreased our time advantage. A classical example is the case of the German Air Force which withheld information on captured British microwave bombing equipment from the German submarine command. Six precious months were thus lost by the Germans in combating microwave *aircraft to surface vessel* [ASV] radar. Perhaps the whole war and history of the world was affected by this instance of the shortsightedness of excessive secrecy.

Though wartime secrecy concerning engineering advances usually serves to keep the wrong people in ignorance, we must concede that peacetime secrecy is more of a problem. Here the element of time and speed is lacking; so if we *assume* that a truly important weapon can be kept secret there is point in limiting complete information to a few people only. Of course, such limitation will automatically retard technical progress, and perhaps retard quantity production in the event of war. But how can we assume that we can keep a secret, when in fact it is exceedingly difficult to find any important weapon or scientific advance that was not the contemporaneous interest of potential belligerents? This generally universal development of "secret" weapons should surprise no one, for creative thinking does not come as a bolt from the blue. It comes from the free interchange of ideas between all manner of people doing all manner of work. Modern radar owes much to virtually all nationalities working for hundreds of years. The atomic bomb roster includes Germans, Italians, French, English, Americans, Canadians, and Austrians, to mention but a few nationalities.

Before the war England, Germany, Japan, France, Italy, and the United States were all closely guarding radar as a highly secret device. By such close control our progress was immeasurably hampered, but to be sure the enemy also probably failed to benefit from our discoveries. At the start of this war our radar was far behind what it could have been, but Japanese radar was still farther behind and that of the Germans somewhat ahead of ours. It is likely that our radar advantage over the Japanese would have been reduced by free publication, while it is interesting to speculate on how soon the whole show would have been given away anyhow under the impact of normal peacetime demands for the facilities which radar offers. The best one can hope for, even with tight security control, is a slight time advantage of a few months to a year or so and there is a very good chance that excessive secrecy, by slowing down production, will actually lose any advantage gained by prior invention.

We can only conclude that in the past, and increasingly so in the future, no nation has had or will have a monopoly on scientific advance. No way is known to keep secret a fact of nature; it is present for all inquiring minds to discover and apply. Of nearly equally dubious validity is the belief that engineering "know-how" can be kept secret to the advantage of the possessor. Only rarely is an important weapon significant in small quantities, and if it requires mass production to be useful it must be designed with the national technical structure in mind. Airplanes, rockets, radars, guns, ships, tanks, radios are a clear reflection of our industrial life and as such hold few real secrets. In fact, our thinking is distressingly influenced by what has been done before, so that under the stress of war we turn again and again to established practice.

Wherein, then, does security lie? Some will argue that large standing armies and full military preparedness are the only safeguard. Others believe in a small, highly trained army of mechanical wizards possessed of an array of push buttons marked with the names of potential enemies. We even hear the attack-now theory which urges us to use our temporary alleged superiority in atomic bombs to wipe out anyone and everyone who might one day wipe us out.

To suggest that all this is unconstructive, hysterical, and even insane is perhaps out of place in a book devoted to the "creative" side of war. But as we remarked earlier, this volume attempts to approach warfare as a whole. By our intensive study of technical warfare during the most destructive war of modern times we, as scientists and engineers, are qualified to speak of more than boxes, knobs, rectifiers, and antennas. We have observed and reflected on the nature of technical warfare and can only conclude that no nation can, by scientific and industrial effort alone, insure itself against annihilation. There is no impregnable defense; there is no guarantee of victory no matter who starts another war.

All we achieve by peacetime military effort is a little time in which to marshal our forces. War, large-scale war, will not strike without warning, without a period of mounting tension and expanding armaments. No nation will go to war without preparations plain for all to see. Pearl Harbor was no surprise; it was a question only of "when" and "where." Before Pearl Harbor the scientists of the country were mobilizing and working at top speed. The Radiation Laboratory, organized in November 1940, had pushed far into microwaves before the Japanese struck and it was microwave radar on shipboard which turned the tide in the sea battles of early 1942. Our strength lay in a healthy scientific and engineering tradition of education; the same tradition which has created our entire industrial life. In any future war it will again be the trained engineers, scientists, industrialists, and administrators who will pull us through; if anyone is left to be pulled through!

1.4 SELECTION AND TRAINING OF SCIENTIFIC PERSONNEL

Coming full circle to our original intention in this chapter, which was to catalogue the essential organs in the military scientific body, we urge that primary attention in all Service laboratories, and in all the military structure, be given to the *personnel* and not to gadgets. It is futile to develop a host of guided missiles at the expense of the broad training of the minds of young engineers and scientists. During the five years of World War II we stopped broad training in physics, chemistry, and mathematics in order to accelerate our industrial output. Now, of all times, we find large programs for all types of weapons, which though they may be stepping stones to the future, will not contribute one iota to revolutionary advance. Young men who should be encouraged to take advanced studies in basic science are tinkering with more of the same gadgets which they worked on in time of war. Peacetime is the time for advance in basic science, for normal industrial pursuits, and for general education. What we must do now is revive a strong interest in the individual, in the broad training of his mind, in a rewakening of his sense of balance. Our success in waging a relatively bloodless, mechanized war has misled many into placing undue peacetime emphasis on the design of equipment rather than on the training of mind, and uncovering new facts of nature.

Military laboratories, and all those engaged in military research wherever they may work, must broaden their intellectual base by holding seminars on general science, by inviting other scientists and engineers to participate in their problems, and by actual attendance at neighboring universities. Perhaps eminent scientists, both industrial and academic, can be induced to accept part-time consulting jobs. Going one step farther, it should be possible to attract capable university scientists to work in military laboratories for short periods; particularly if rare or costly equipment is thereby made available to them. Of course, freedom to publish facts-of-nature must be fully assured before capable scientists will become interested. What the military laboratory gets from this generous attitude is contact with a fresh and perhaps stimulating mind. Whatever else it gets in the form of tangible results is an extra dividend.

We have dealt at length with the problem of getting scientific ability and outlook into the military establishments, and we have implied that always there will be many more scientists outside the pale than in, and desirably so. The country as a whole is a vast scientific reservoir which must be understood by the military if it is to be drawn upon. Defense of country is every citizen's responsibility and prerogative. There must be no resentment if a civilian scientist exercises that prerogative and tries to discover all he can about military needs. He is no more likely to sell out his country than a man in uniform; and he is often more sensitive to his secrecy obligations than is the military man who may not know the entire technical story.

Nor is it enough simply to tell the scientist whatever he wants to know. One must go farther than this, for the scientist does not know in advance what he should be told in order to arrive at a new weapon as yet not conceived. The only way known to get results is for the military liaison officers to help the scientist live a vicarious combat existence in all details except actually slogging through the mud. Even the latter is sometimes stimulating, though generally the would-be inventor comes out with the conviction that what is most needed is more rugged equipment of the existing types. Since this is just the point of view of many military men, there is little to be gained by urging the scientist to get too close to his problem. A certain degree of detachment has always been one prerequisite to a major advance.

Even so, the military agencies must avoid detaching the civilian scientists too completely from the experimental laboratory of war. There existed a strong tendency for military men to shield the civilian laboratories from the tactical problems of war. Either by implication or direct statement the civilians are informed that logistics, strategy, and tactical maneuver are not to be understood by them. A great deal has been said, however, about the cold, the mud, the need for simplicity, and other self-evident truths. An approach such as this is bound to induce the scientist merely to make improvements in existing equipment and to dull his sensibilities for more creative work.

One last remark on the endless subject of free interchange concerns information on enemy developments. Nearly everyone, in and out of military circles, deplored the very strong tendency to treat captured enemy secrets as "especially secret." Why this should have been established policy is beyond logic, because no one gained by it except the enemy. Countermeasures which scientists could easily have developed were slow to materialize because only the intelligence officers were in possession of the enemy data. A policy of immediate and accurate reporting of *all* enemy technological and scientific advances would have helped this country's research and perhaps led to more successful countermeasures. Even if it be argued that the "uncontrolled" scientists might have "let leak" to the enemy the fact that we knew of his activities, there would be little, if any harm done. In such an event, the enemy could either abandon his equipment — a gain for us — or somehow change its characteristics. To accomplish the latter in any useful and timely way is, in the case of radar at least, a very difficult engineering feat. Just the engineering manpower thereby diverted is, in itself, a serious drain on a country.

It may be argued that disclosure of captured technical data may jeopardize our counterintelligence service if the enemy becomes aware of our activity. A clear answer exists here because such disclosure would not be broadcast to the enemy; it would be made to the scientific laboratories already accustomed to safeguarding their own secrets. The enemy's first knowledge of a leak in his own secrecy screen would be the appearance of an attempted countermeasure. Since considerable delay would normally exist between uncovering an enemy's secret and developing and applying a countermeasure, there would be a good chance for our counterintelligence agents to cover up. But in the last analysis one may well ask, "Why go to all the trouble to uncover the enemy's technical secrets if no countermeasure is forthcoming? If valuable information is to be withheld from those who can effectively utilize it, why jeopardize the lives of our counterintelligence agents?"

1.5 PROBLEMS OF COOPERATION BETWEEN CIVILIAN SCIENTISTS AND MILITARY AGENCIES

We turn now to other problems of cooperation between civilian scientists and the military agencies. Assuming that the civilian agency, be it industrial or educational, has devised some new scientific weapon, there arises the problem of demonstration and proof testing. Perhaps it was inescapable in the stress of war that our Armed Services were badly organized for testing new equipment quickly and intelligently. Certainly there was very little military personnel adequately trained for tactical testing of radar; for by the very nature of any new advance there will rarely be available personnel with sufficient detailed knowledge to assess a new weapon competently.

One would think that this is so obvious as to call for a close working agreement between the military proving grounds and the external scientific agencies whence spring the new devices. On the contrary, the civilian was sometimes regarded with great distrust, not to say suspicion, of his motives in helping the testing agency. Charges of biased judgment and super-salesmanship only served to obscure the fact that the military testing agencies lacked the personnel, equipment, and experience for keeping pace with technological warfare. There were some notable exceptions to this rule. Toward the end of the war, after four years of striving, a definite improvement was in evidence. Can we not recognize the importance of welding all elements into one powerful team? Must we again take four years to develop scientific teamwork?

Some proving grounds encourage the scientist just to stay around and keep the equipment running; but rarely is the scientist encouraged to study the tactical employment of his instrument of war. Instead, this is the prerogative of junior officers with less technical experience and little background in battle. Naturally it is not easy to attract outstanding officers to proving-ground work, for the glory is slight and advancement slow. In military circles there is no tradition of technical understanding and objective scholarship. Headlines go to colorful, dashing officers who take their technical weapons as a matter of course.

But the country does not lack engineers and scientists able and eager to help keep our country strong. It is necessary, however, to develop the proper perspective which will bring scientific training into contact with the technical problem of introducing new weapons.

Going on now to the problems of combat use of equipment that has been hurried through the proving ground, we again find an important, but transient, role for the scientist and engineer. Training methods must be set up, and if the weapon is fairly radical, much valuable time can be saved if the inventing scientist will but give a little attention to assisting the training commands. Education is always slow, but if it is confined to the usual chain process where one man tells his neighbor and in turn the neighbor passes it on, there is a good chance for confusion and delay. This past war found civilians taking an active, if belated, part in training. Generally they were welcomed and found very helpful.

A lesson learned slowly during the five years of radar introduction was the immense value of training aids and especially scoring devices. In bombing and fire control our hitting power would have been greatly increased if simple scoring methods had been more readily available. Imagine training a rifleman without some sort of score keeping, and yet that was virtually the situation in radar bombing and aerial gunnery. It was no exaggeration to call radar bombing "blind bombing." And yet, scoring methods were developed which, with adequate military backing, could have seen early and wide employment. Had these been pushed there is little doubt that our air force could have been several times more effective.

It should be axiomatic that training, training aids, *and* scoring aids should receive early and competent attention. Nor should scoring aids be confined to the training phase alone. Training cannot duplicate actual combat, and it is therefore essential to establish and to keep informed on the combat accuracy of any equipment, new or old. Combat accuracy evaluation will do much to keep up a man's interest and morale and at the same time will give information of great value in planning operations. The generally increased feeling of responsibility in all quarters should materially increase the effective striking force. In aerial gunnery, only a small percentage of the bullets came anywhere near the target so that even a small increase in accuracy should bring important results. Radar bombing was notably inaccurate and much worse than it needed to have been. Expressed in terms of concentration of bombs on the target we were only about 2 per cent as powerful as we could have been. Though accuracy expressed in this way is by no means the whole story, and it would be unfair to charge that our Air Force could have been fifty times more powerful with the same cost to the country, it is the considered opinion of many that better trained operators and combat scoring would have had a powerful effect on our bombing offensive.

Along with scoring aids for combat evaluation it is imperative to have a team of analysts capable of interpreting combat results and making recommendations for future employment. A subject as large and important as operations analysis cannot be profitably discussed here. We suggest that our war experience was only moderately successful in so far as radar was concerned and suffered from very poor liaison between interested agencies. Too few radar experts were interested in analysis, and too few analysts knew anything about radar.

A sweeping generalization of this nature cannot be dismissed by saying that war will always bring about a manpower crisis; our troubles were due largely to inadequate appreciation of the problem as a whole. Assuming that future wars will raise similar problems we can hope that less time will be lost in getting everyone off on the same foot.

In the chapters to follow the reader will find evidence of the strength and weakness of civilian scientific laboratories. In ways not easy to prove, but visible nonetheless, he will see reflected in equipment design and philosophy the practical problems of coordinating hundreds of minds working under different conditions. What may seem to be a technical fault may, in fact, be attributable to the complexities of human endeavor. And again, a particularly elegant handling of a knotty situation may have been synthesized from the ideas of many minds.

Radar was the fruit of several thousand scientists and engineers both in and out of military organizations. The chapters to follow cannot adequately express the importance of each contributor to the whole. We have learned much about cooperation and the difficulties of achieving it. We are grateful to all those agencies, military and industrial, who made our job easier by their generally friendly spirit of assistance. What we have said in criticism of civilian-military cooperation has been said in the hope of improving future relations. Clearly these relations have been essentially healthy, even if sometimes erratic, because this team did produce and employ in combat vast quantities of good equipment. It is only because war is so terribly inefficient that much room is left for improvement and criticism.

PART I

RADAR MEANS FOR DETECTION OF SURFACE VESSELS FROM AIRCRAFT

Chapter 2

FUNCTIONS OF ASV RADARS

2.1 GENERAL DESCRIPTION

Aircraft to surface vessel [ASV] radar is an airborne radar whose primary function is to detect objects of interest (commonly called targets) on the surface of a body of water and to present adequate range and bearing data so that an observer in the aircraft may guide the aircraft close enough to a detected object for visual contact. All the ASV radars discussed in Part I are pulsed radars.

2.1.1 Target Detection

A beam of very high-frequency radio waves is directed from the aircraft and covers an area on the surface of the water which is large compared with the objects to be detected. In general, this is done by use of a parabolic reflector, with its associated antenna, which rotates through 360 degrees. Very little radio-frequency energy is reflected back from the surface toward the radar's receiving antenna if the surface of the water is relatively flat. Moreover, the objects of interest are usually good reflectors presenting a favorable aspect for reflecting a readily detectable amount of energy back to the radar. Thus, the primary function of ASV radar is attained rather easily under good conditions. Under adverse conditions, however, such as rough air and rough sea, and when the object of interest happens to be small, this function becomes extremely difficult to attain. When the sea is rough, the waves themselves reflect the radio waves back to the radar, causing a background of fluctuating signals. This background, commonly called sea clutter or sea return, tends to obscure the desired signals, and small targets may be completely lost. Sea clutter, then, often becomes a limiting factor in the usefulness of an ASV radar system. Consequently a criterion of good design in ASV radars is the extent to which sea clutter is eliminated or minimized.

2.1.2 Navigational Feature

The targets (objects of interest) which ASV radars are designed to detect may be shipping, buoys, islands, reefs; in fact, they may be practically anything on the surface of the water or the shoreline itself. It is implied, therefore, that an ASV radar serves in part as a navigational aid. Indeed, the more modern ASV radars, with *plan position indicator* [PPI], and increased resolution, have tended to emphasize the navigational feature as a major function. Since shorelines, as a rule, give excellent radar signals, the map-like type of presentation afforded by ASV sets equipped with PPI makes such sets invaluable navigational aids. The use of radar for bombing, as described in Part II of this book, was largely an outgrowth of the use of ASV radars for navigation.

2.2 USES OF ASV IN PEACETIME

2.2.1 Types of Missions ASV Radars May Perform

Some of the peacetime uses of ASV radar are fairly obvious. Rendezvous at sea between ship and plane is easily accomplished when the plane is equipped with such a radar. The value of such a rendezvous is made evident by an incident in the North Atlantic. A critically ill merchant seaman was removed from a freighter to a Coast Guard PBM flying boat and flown safely to land for medical attention. The PBM's ASV radar had guided the plane to the ship through a heavy fog. Rescues at sea and deliveries of medical supplies and personnel to ships and small islands are other life-saving missions for which ASV radars are especially adapted. A less spectacular and more commonplace type of mission for the peacetime ASV radars is the rendezvous at sea for the purpose of transferring mail.

2.2.2 Beacons

Radar beacons[6] have proved a valuable adjunct to ASV radars during the war, primarily as navigational aids, and doubtless will continue to do so. The radar beacon is designed to respond by sending out a pulse or sequence of pulses whenever it receives a pulse from a radar whose transmitter frequency falls within a certain frequency band. Beacons have the additional feature that they respond only to transmitted pulses whose pulse durations are within certain limits. This feature enables the operator of the radar to exercise control over the beacon, so that it will respond to his radar only if the operator so desires. The response of the beacon is usually coded for identification purposes. Also the beacon's transmitter frequency is out of the frequency band of the radar's transmitter to prevent radar signals from obscuring the beacon response. Some of the specialized requirements of such a radar beacon are immediately evident. For example, its receiver bandwidth must be fairly large and its antenna pattern broad. Correspondingly, design requirements are imposed on the ASV radar to insure appropriate interrogation of and reception from the beacon. Beacons are located usually at favorable shore locations or on ships.

Some of the uses of ASV radars mentioned above would be enhanced by the use of beacons. The mail transfer operation, in particular, is one which would be especially benefited by the use of a radar beacon on the ship, since it would avoid confusion if other ships happened to be near the rendezvous area and since it would eliminate the sea clutter problem.

2.3 MILITARY APPLICATIONS

2.3.1 Routine Patrol

The chief military function of ASV radar during the war was for patrol, usually routine in nature, to insure that no enemy ships entered the area under patrol. It was largely through performance in missions of this type that the ASV radars earned the appreciative soubriquet "the eyes of the fleet." Not only were the radars useful during time of poor visibility, but even on the clearest days they could be relied upon to detect ships of all sizes at greater ranges than those at which they could be detected visually. For these reasons, fair weather or foul, the ASV patrol or search missions were flown on routine schedules in so far as possible. As a rule, medium and heavy bombers were used in this work, though small bombers and torpedo bombers were also used to advantage. In order that the plane be able to patrol as large an area as possible, it is usually desirable that the two paramount design features of ASV radars be maximum range performance and minimum weight. Since these two features impose rather contradictory requirements, the design of an ASV radar set always involves a certain amount of compromise between them.

An ASV radar search mission will be described briefly, beginning with the briefing of the pilot. For the purposes of this discussion, briefing for such a mission includes information regarding friendly vessels in the area and instructions regarding such things as weather conditions and radio watches. The radar operator, who may also be the navigator or radio operator, may be briefed separately or with the pilot, or he may simply receive such information from the pilot. During the mission itself the radar operator reports to the pilot upon noting a signal. (Some ASV radars provide a second scope for the pilot, though this is not usually the case.) If there is any suspicion that the signal is from an enemy vessel the pilot informs his operations base. Following this initial contact any of a great variety of maneuvers may be made subject to weather conditions, time of day, and the prevailing tactical situation.

Frequently the plane is ordered to "home" on the suspicious vessel for the purpose of identifying it and possibly to attack it. This homing operation consists of flying a course as directed by the radar operator to intercept the target; it is an important feature in ASV radars.

2.3.2 Submarine Detection

One of the most important roles played by ASV radars during the war was in antisubmarine warfare. Probably the earliest successful operational use of American ASV radars against the enemy was in patrolling the Eastern Seaboard area of the United States and the Caribbean area during the most of 1942, when the German submarines constituted a very serious threat to Allied shipping in the Atlantic. The tactical situation existing during these operations was such that an attack was initiated as soon as it was established that a suspicious signal came from an enemy submarine. This attack was usually carried out with depth bombs. Although confirmed sinkings of the submarines were few compared with the number of attacks made by the planes themselves, the effect upon the morale of the submarine crews, together with the sinkings made by destroyers and subchasers called to the scene by these planes, soon caused the submarines to withdraw to happier hunting grounds, at least temporarily. A race of armament and tactics between the German submarine experts and American and British antisubmarine experts soon was under way.

The one most obvious tactic for a submarine to employ, when a hostile plane is approaching, is to dive beneath the surface where the submarine is safe from detection by eye and by radar. One of the first important countermeasures was the use of a magnetic device for locating the submerged submarines. This device, known as *magnetic airborne detector* [MAD], was a sort of airborne magnetometer. Its range, only a few hundred feet, was short compared with the radar's range, but the fact that it could detect submerged submarines made it an important adjunct to ASV radar, by enabling the plane to drop depth charges on the submarines and to drop patterns of marker buoys to aid friendly vessels called to the scene. Later in the war, sono buoys were used to replace the MAD and marker buoys.

One of the earliest antiradar devices used by the submarines was a receiver for detecting radar signals from the aircraft. These receivers were sufficiently sensitive to detect such signals at ranges comparable to, and often exceeding, the ranges at which the aircraft could detect the surfaced submarines. The chief countermeasure against these receivers was a shift to radars of much higher frequencies, the microwave radars, and having these radars operate over a sufficiently large frequency band to decrease considerably the probability of the receivers detecting them. A second measure designed to thwart the Germans' microwave receivers was the Vixen attachment for ASV radars.

Normally if a submarine is listening to a plane's radar and if the plane is approaching as in a homing run, the power of the received signal varies inversely as the square of the distance between submarine and plane. Thus, the variation in the power of the received signal gives the submarine its cue as to whether the plane is homing on the submarine. The Vixen attachment is a cam-operated variable attenuator driven by a motor so as to make the transmitted power vary as a function of range, in such a manner that the power received at the submarine remains constant or decreases as the plane approaches. The operation of Vixen during a homing run is explained by the following equations:

$$p_p = \frac{kP}{R^4} \quad \text{and} \quad p_s = \frac{k'P}{R^2}$$

where P is the transmitted power, p_p the power received at the plane due to reflection from the submarine, p_s the power received by the submarine receiver, R the distance between plane and submarine, and k and k' are positive constants depending upon receiver and antenna characteristics. Now suppose the Vixen cam is constructed so that it varies P in such a manner that the relation $P = \alpha R^3$ is valid, where α is a positive constant. By substituting in the above equations,

$$p_p = \frac{\alpha k}{R} \quad \text{and} \quad p_s = \alpha k' R.$$

Thus, the power received at the submarine decreases as the range decreases (presumably causing the listener on the submarine to believe the plane is going away), whereas the signal received at the aircraft increases as the range decreases, though not so rapidly as when the Vixen is not used.

Actually, the Vixen device received little use, largely because other measures, such as the frequency change mentioned above, together with the destruction of enemy bases, factories, and other equipment on the European continent, succeeded in minimizing the submarine threat.

The last important device used by the German submarines in defense against ASV radars posed serious problems for the Allies. This device, known as Schnorkel,[7] was a revolutionary one in submarine operations, in that it enabled the submarine to stay submerged almost indefinitely and also to travel under water at much faster speeds than previously. The portion of the Schnorkel above the water line is sufficiently small to make it a poor radar target, especially when covered with radar absorbent material or in the presence of much sea clutter. Chief features of ASV radar design to counteract the Schnorkel were narrow-beam antennas and shorter pulse duration (to increase the signal-to-sea-return ratio), and special receiver circuits for minimizing the effects of sea clutter.

The use of escort carriers with convoys in the Atlantic widely extended the area under surveillance of ASV radars and added greatly to the demise of the submarine menace.

2.3.3 Other Uses

Another important role of ASV radar during the war was its use by blimps for aiding in convoy escort duty. It was used to aid the blimps in making contact with their convoys and in patrolling the area around the convoys for submarine detection.

ASV radars were employed successfully on numerous occasions for rescue at sea of survivors of sunken vessels and of planes forced down at sea. A simple, but extremely useful contrivance, adopted for assisting the radar in such missions is the collapsible corner reflector for use on life rafts. A corner reflector consists of three microwave reflectors (for example, fabric knitted from cotton thread which is wrapped with a silver-plated spiral) placed at right angles on an aluminum framework forming the corners of a box. Since life rafts make rather poor radar targets and corner reflectors make good ones, if correctly oriented, these reflectors increase greatly the range at which the rafts can be detected by radar.

It was mentioned above that ASV radar served an important function in guiding the plane to its target. In fact, such operations are usually successful in guiding the plane almost directly over a ship. In general, however, such homing runs carried out with the aid of ASV radar alone are not of the precision requisite for successful bombing, though the radar is doubtless sufficiently accurate for facilitating some of the functions mentioned above, such as the dropping of supplies. The homing run may well terminate in a bombing run, in which the actual dropping is done with the aid of an optical bombsight or a radar bombing attachment of one of the types to be described in Part II.

Chapter 3

MEANS OF ASV DETECTION

Two types of *aircraft to surface vessel* [ASV] radars widely used by the United States were those operating at transmitter frequencies below 600 mc (long wave) and those operating at transmitter frequencies above 3,000 mc (microwave); the former were the earlier type, the latter the more recently developed. There were no ASV radars of importance with transmitter frequencies between these limits.

3.1 SEMIDIRECTIONAL EQUIPMENT

A characteristic difference in external appearance of the microwave ASV radars and those of lower frequencies is in the type of antennas used. Microwave ASV radars use parabolic or modified parabolic reflectors for directing beams of high-frequency electromagnetic waves, and scanning systems to enable the beams to cover large areas of the surface and to obtain bearing data on reflecting objects. The lower-frequency radars employ fixed directional antenna arrays of the Yagi type,[11a] for directing the waves and obtaining bearing information on reflecting objects; the amplitudes of the signals received from the objects on two fixed antennas are compared. A typical Yagi array for ASV use consists of one driven antenna, one parasitic antenna, and two parasitic director antennas. The major portion of the present chapter is devoted to microwave ASV radars. First, however, two of the lower frequency radars which were used rather widely and successfully are described.

3.1.1 Search and Homing Antenna for ASVC Radar

The first ASV radar to be used extensively by the United States forces was of British and Canadian design, and operated on a nominal frequency of 176 mc. For general search use it employed a single wire transmitting antenna and two receiving antenna arrays aligned with main lobes extending directly to port and to starboard of the aircraft (Figure 1A). For homing, it employed a Yagi transmitting antenna array, located near the nose of the aircraft and aligned so that its main lobe was directly along the axis of the aircraft, and its receiving antennas located under each wing of the aircraft aligned so as to have overlapping lobes, as illustrated in Figure 1B. This radar was called ASVC. An American redesign of this equipment for the Navy was known as ASE.

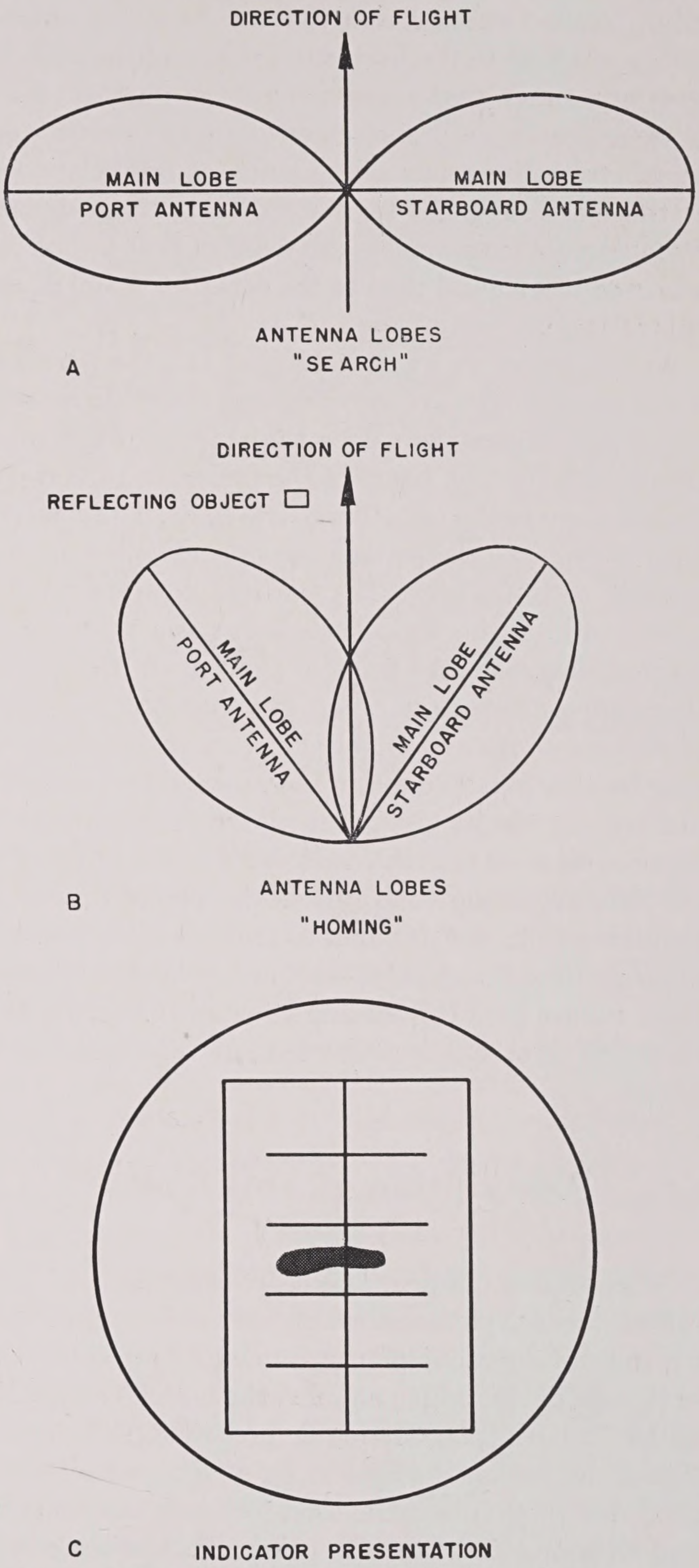


FIGURE 1A, B, C. Low-frequency ASV antenna patterns and indicator.

3.1.2 Data Presentation in Longer-Wave ASV Radars

The ASV indicator, typical of the longer wave ASV radars, employs an electrostatic cathode-ray tube. A linear saw-tooth sweep, synchronized to cause the electron beam to start upward each time the transmitter fires, is applied to the vertical plates of the tube. Signal voltages from the two receiving antennas are applied to the horizontal plates of the tube in such a manner that signals from the port antenna cause deflections of the electron beam to the left, and signals from the starboard antenna cause deflections of the electron beam to the right. A motor-driven switching device connects the receiver first to one receiving antenna and then to the other for equal intervals of time.

As illustrated in Figures 1B and 1C, the port antenna receives more reflected energy from the reflecting object shown than does the starboard antenna. Hence, the electron beam of the indicator tube is deflected more to the left than to the right. The relative sizes of the two deflections are an indication of the bearing of the object. The vertical position on the tube at which the deflections occur is a measure of elapsed time since the firing of the transmitter and is therefore a measure of range. By changing the slope of the saw-tooth sweep voltage, various range scales may be selected. The radar operator guides the plane in a homing run by giving the pilot directions to keep on a course such that the deflections to the left and to the right are of the same amplitude. The technique of switching from one antenna to another as a means of accurate direction finding is known as lobe-switching. Most radars used for obtaining accurate bearing and elevation data use a refinement of this same technique.

3.1.3 Description of ASB Radar System

A significant improvement in operation of ASV radars of the type described above was brought about by the development of the duplexer,[3] an electronic switching device which enabled the use of a single antenna for both transmitting and receiving. The use of this device makes the nose array no longer necessary. First one wing antenna is used for both transmitting and receiving and then the other. This arrangement permits a more efficient use of the transmitted power. The U.S. Navy's ASB radar, which employed this principle, was one of the most successful of all ASV radars. Figure 2 shows a block diagram of the major units of the ASB radar.

The indicator used with the ASB radar is similar to the one described above. The nominal transmitting frequency is 515 mc. The pulse duration is approximately 2 μsec and its pulse recurrence frequency approximately 400 pulses per second. The motor-driven antenna switching unit switches from one antenna to the other at a rate of thirty times a second. A novel hydraulic control system enables the use of the same antennas for search and for homing. In normal search operation the antennas are aligned so that their beams point at right angles to the direction of flight. In homing, the antennas are aligned so that their beams overlap, as in Figure 1B. By the use of the hydraulic control system the operator causes the antennas to move from the search position to the homing position. By continually using the control and by properly maneuvering the airplane, a good pilot and radar operator team can make the antenna beams scan a wide area quite effectively. Although lacking a number of desirable features of the microwave radars, the ASB's reliability, versatility, and light weight made it one of the most useful of all ASV radars.

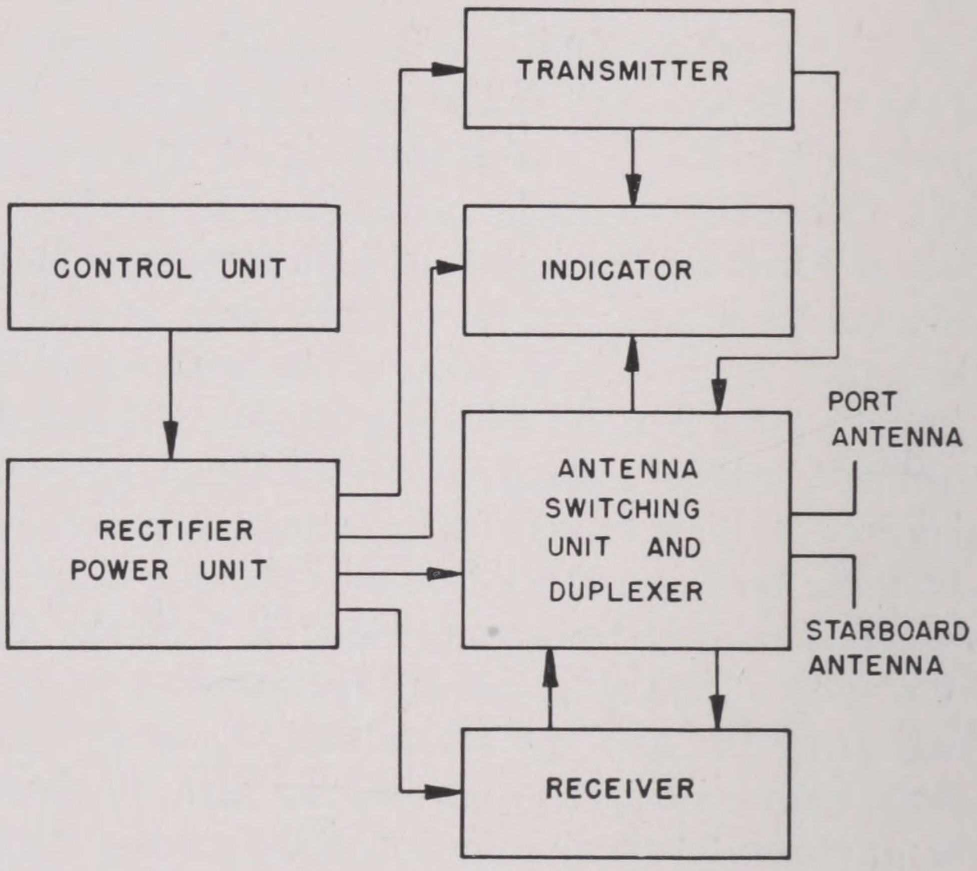


FIGURE 2. Block diagram of major units of ASB radar.

3.1.4 General Characteristics of Long-Wave Radars

Radar beacons for use with these longer-wave radars are coded by means of motor driven coding wheels which key the beacon transmitter in a periodic sequence at a rate of about 1 cycle per second. Each radar pulse received by the beacon causes the beacon to send out a responding pulse unless the coding wheel shuts it off. The radar operator identifies the beacon by the fluttering sequence of the signal.

It will be noted that none of these longer-wave ASV systems gives quantitative bearing data, although they are adequate for the homing function. For this reason, these radars are far inferior to the microwave radars as navigational aids.

Under good operating conditions, ASV radar systems of the type described above give excellent performance in so far as detection of large objects at long ranges is concerned. The ASB radar described above is quite suitable in this respect, although its *average* output power is only about 12 watts. The usefulness of these radars, however, is limited by their lack of resolving power. The degree of resolution of a radar determines its ability to separate the signals received from objects close together, both in range and in azimuth. In an ASV radar, it also determines its ability to discriminate between a desired signal and undesired sea clutter. Resolving power is primarily a function of the area of the surface illuminated by a single pulse. It is inversely proportional to the antenna beamwidth and inversely proportional to the pulse duration. It is virtually impossible to secure a narrow beam comparable to that used in the microwave radars (less than 10 degrees between the half-power points) at the frequencies employed by the longer-wave radars, with an antenna capable of being airborne. Although later models of the ASB radars incorporated a number of anticlutter[4a] circuits developed for minimizing sea return, the performance of these radars in the detection of small objects in a rough sea left much to be desired. Against the Schnorkel, for example, the ASB radar is almost useless.

3.2 MICROWAVE SCANNING SYSTEMS

Scanning systems used with the microwave ASV radars give these radars an important feature not obtained with the longer-wave ASV radars, namely, quantitative bearing information. The high-gain parabolic reflectors used for directing the microwave beams result in beams sufficiently narrow that comparatively accurate bearing data are readily obtained. Microwave ASV radars generally use mechanical scanning systems for moving the beams in such a way as to illuminate efficiently a large area of the surface in a periodic fashion (either a 360-degree scan or scan of a sector, 60 degrees for example, in front of the aircraft).

3.2.1 Presentation of Data

The microwave ASV radars generally employ one of two types of data presentation developed for making adequate use of the accurate bearing information obtained. One type, the *plan position indicator* [PPI], is a polar coordinate system in which the position of the aircraft is the pole. Signals received from objects produce bright spots on the tube. The distance from the pole to a spot is proportional to the slant range to the reflecting object, and the angular position corresponds to the bearing of the object. The other type of presentation, known simply as B scope presentation, is a rectangular coordinate system in which bearing and range are abscissa and ordinate respectively. This type of presentation is used chiefly by radars designed for installations where it is convenient to scan only the area in front of the aircraft. In both types, the received signals are applied to a cathode-ray tube in such a manner as to modulate the intensity of the electron beam. The cathode-ray tube screens used with both types of presentation have fairly long persistence so that the bright spots do not fade out completely between successive scans.

NAVIGATIONAL FEATURE

The PPI display is a fairly accurate map, the main distortion being due to the fact that slant range is used rather than range measured along the surface. The distortion is negligible for most ASV work since the planes usually fly at low altitudes. The sweep applied to the cathode-ray tube is modified in some systems in which extremely high fidelity in mapping is desired, so as to approximate ground range data. The B scope display is a distorted map, the distortion being greatest at short range. Although it is objectionable in some respects, the increased angular resolution at close ranges afforded by this distortion is often found desirable in the final stages of a bombing run. Both types of presentation bear sufficient resemblance to maps that coast lines, islands, lakes, rivers, and other geographical features may be readily identified. The ASV radars are, therefore, most valuable navigational aids. (For a more detailed discussion of radar mapping systems and of the types of indication employed, see Section 7.2.)

OTHER FEATURES

In addition to the geographical data mentioned above, other types of information obtained by these radars are often of value. Among these are signals from storms, from nearby airplanes, and the altitude signal. The altitude signal usually appears as a ring on the PPI and as a horizontal line on a B scope, and is due to the energy scattered more or less at random from the radar antenna and reflected back from the nearest point on the surface beneath the aircraft.

Beacons for use with microwave ASV radars operate similarly to the beacons used with the longer-wave ASV radars, with the exception that the coding technique is different. This difference is due to the different types of presentation used in the two types of radars. The microwave beacon employs a pulse duration discriminator, so that it responds only to pulses whose durations are approximately 2½ μsec. By selecting the pulse duration the radar operator can control the response of the beacon. The controls of the ASV radar customarily are such that when the operator wishes to interrogate the beacon, he operates a control which simultaneously selects the correct pulse duration and also tunes the local oscillator in the radar receiver to the correct frequency for receiving the beacon signal. When the beacon is interrogated, each radar pulse causes the beacon to respond with a definite sequence of pulses. The number of pulses of the sequence and the time interval between pulses of the sequence represents a code. The time interval between the firing of the radar pulse and the reception of the first pulse of the beacon sequence represents the range of the beacon when displayed on the radar's indicator in the same manner as ordinary signals. Similarly, the bearing of the signals received from the beacon indicate the bearing of the beacon, since the beacon responds only when the radar antenna is pointed toward it (see Chapter 10). At close ranges, the beacon may respond to side lobes of the antenna pattern, but the operator, by correct use of the receiver gain control, can usually distinguish between the response to the main lobe and the responses to these side lobes.

3.2.2 Comparison with Over-Land Scanning Systems

Scanning systems employed by microwave ASV radars are essentially the same as those used by the radars developed primarily for bombing inland targets. The antennas, however, are usually somewhat different in the two types of radars. The chief reason for this difference is that the radars designed for bombing inland targets must be capable of good mapping of the ground from high altitudes, whereas ASV radars are generally used at comparatively low altitudes. In order that a radar give good illumination of the ground from high altitudes, the antenna beam must be fanned rather broadly in the vertical plane. This broadening of the beam is accomplished only at the sacrifice of antenna gain, and hence a reduction in the maximum range obtainable. In ASV radars, some fanning of the beam in the vertical plane is usually desirable for good performance at close ranges, but since these radars are usually operated at lower altitudes, and since good performance at long range is a primary design consideration, the beam is usually fanned much less than in the radars designed primarily for bombing land targets. The AN/APS-15 radar, which was used extensively for both over-land bombing and for ASV patrol work, provided different antennas for the two functions.

Chapter 4

DESIGN CONSIDERATIONS

4.1 BASIC DESIGN CONSIDERATIONS

The design of a microwave *aircraft to surface vessel* [ASV] radar must necessarily represent a compromise between performance objectives and physical limitations. The objectives include good search performance at both long and short ranges and high range and azimuth resolution; the physical limitations are those of size, weight, and power consumption. The basic design considerations essential to effecting a satisfactory compromise between these objectives and limitations are given in the present section. In addition to the basic features discussed here, there are many other design considerations affecting the general utility of the radar. Among these are reliability, simplicity of operational controls, facilities for test and maintenance, and facilities for accommodating various useful attachments (such as bombing and rocket-firing computers, and *identification of friend or foe* [IFF] equipment).

4.1.1 Azimuth Resolution

In Section 3.1.4 we indicated the importance of high resolving power in ASV radars, noting its desirability for separating signals received from objects close together and also for discriminating between a desired signal and undesired sea return. The azimuth resolution of a radar increases as the antenna beamwidth in the horizontal plane decreases. The beamwidth is the angle between the two half-power points of the antenna pattern.

In a microwave ASV radar antenna the feed is placed approximately at the focal point of a parabolic reflector. High-frequency electromagnetic waves are radiated from the feed to the reflector, which concentrates the waves into a beam of energy. The beamwidth of such an antenna is directly proportional to the wavelength λ and inversely proportional to the width of the reflector. Hence, maximum azimuth resolution is obtained by using the widest possible antenna and the shortest possible wavelength. However, antenna size and weight are limited by the aircraft in which the radar is to be used and the type of installation contemplated. The limitations on wavelength are not so readily apparent. In the early stages of development of microwave radar, the efficiency of many r-f components decreased rather rapidly as the wavelength decreased. However, at the close of World War II, the long-range performance of most X band ASV systems was about as good as with S band systems of about the same weight and power consumption, since both were capable of detecting medium sized vessels at distances comparable to the horizon distance at the altitudes favored for ASV operations. K band systems at that time were definitely inferior in long-range search performance because of (1) the limited output power of K band transmitting tubes, (2) the relative inefficiency of some of the r-f components, and (3) the attenuation of K band waves by moisture in the atmosphere.

4.1.2 Pulse Duration

Two of the objectives in ASV radar design, good long-range search performance and good range resolution, are largely incompatible with each other in so far as pulse duration is concerned. The degree of resolution in range is fundamentally limited by the pulse duration — the shorter the pulse the greater the range resolution. Long-range search performance, on the other hand, varies with pulse duration in an opposite manner — the greater the pulse duration, in general, the greater the range at which a given object may be detected. More explicitly, the minimum discernible signal detectable by the receiver varies inversely with the product of the pulse duration and the square root of the recurrence frequency, provided the receiver bandwidth is kept at the optimum value for the pulse duration. In general, maximum range at which a discrete object may be detected varies inversely with the fourth power of the minimum discernible signal, provided the peak power is kept constant.[4b] It is usually more expedient to use different pulse durations rather than to select a pulse duration both for long-range search and for resolution. The pulse recurrence frequency and maximum sweep range are usually varied simultaneously with the pulse duration. Average output power may then be kept fairly constant. If its average output power is kept fairly constant, the radar modulator is, in general, considerably simplified, and the transmitting frequency is usually more stable. Also, each change in pulse duration alone adds complexity to the modulator as well as to the control circuits. Furthermore, if the receiver bandwidth is adjusted to its optimum value for each pulse duration used, the receiver becomes very complex indeed. In practice considerable compromise must be made in receiver bandwidths. At present, no airborne ASV receiver uses more than two bandwidths.

Additional factors influencing the choice of pulse deviations, recurrence frequencies, and sweep lengths are now considered.

The maximum range $R_{\max}$ at which useful informa tion is obtained is fundamentally limited by the pulse recurrence frequency ν_r according to the formula,

$$R_{\max} = \frac{c}{2\nu_r},$$

where c is the velocity of propagation of the electromagnetic waves (approximately 186,000 statute miles per second). This insures that long-range signals do not appear on second or even on later sweeps. Actually, $R_{\max}$ is considerably less than the value given by this formula, since the formula makes no allowance for the time required for the sweep on the cathode-ray tube to return to its initial position, nor does it allow for tolerances in circuit components.

Regardless of the degree of resolution of which a radar is capable, we are making full use of its resolving power only if the data are presented on the tube in the form of a map of sufficiently large scale — in other words, only if a sufficiently short range sweep is used. If a 100-mile sweep is used in normal *plan position indicator* [PPI] presentation, and if a standard 5-in. cathode-ray tube is used as the indicator, then the map obtained has a scale of 40 miles to the inch. High resolution is impossible in such a case. As a fairly typical example, suppose that a 100-mile sweep range for search is desired, maintaining an average power output of 40 watts. This may be accomplished by using a 2-μsec pulse duration and a recurrence frequency of 800 pulses per second. (Some PPI presentation schemes would require a considerably lower recurrence frequency because of a long sweep recovery time.) The peak power output is 25 kw, obtained from the relation $P_{\text{avg}} \times 1/\nu_r = P\tau$, where P_{avg} is the average power, ν_r is the pulse recurrence frequency, P is the peak power, and τ is the pulse duration.

Essentially the same average power output as well as peak power output can be maintained, and good range resolution obtained when a short range sweep is used, by using a recurrence frequency of 3,200 and a pulse duration of ½ μsec. This combination gives a resolution in range about the same as the azimuth resolution obtainable at a slant range of 5 miles with an antenna beamwidth of ½ degree. (It would require an antenna 15 ft wide to obtain such a beamwidth at X band.) Targets separated in range by about 250 ft can be differentiated. The maximum range obtainable with this combination is about 25 miles, a fairly useful range for submarine search in modern ASV systems. For some uses, such as accurate bombing and detailed presentation of harbor installations, a much shorter range sweep presentation is desired; but little is gained, in comparison to the cost in complexity of the system, by further increasing the recurrence frequency and decreasing the pulse duration. In the example just cited, the peak pulse power could have been kept the same, and the pulse duration decreased without increasing the recurrence frequency. In this case, only one-fourth the average power used in the long-range search operation is available, so that some of the weaker signals from close objects probably would be missed.

4.1.3 Stabilization

Microwave ASV radar design often involves consideration of various techniques for stabilizing the antenna. Under ordinary conditions, none of these stabilization techniques is a necessity in enabling the radar to carry out the primary ASV functions of detection and homing. Moreover, most of these techniques add considerably to the weight and power consumption of the radar. The chief virtues of these techniques are that they make the operator's job much easier and improve the performance of the radar under adverse conditions and for some specific applications. These virtues are of sufficient importance to warrant description of some of the stabilization techniques which have been found useful in ASV radars.

LINE-OF-SIGHT STABILIZATION

The object of line-of-sight stabilization is to keep the antenna beam directed to secure good illumination of the surface of the ground or sea regardless of the changes in attitude of the aircraft. The use of line-of-sight stabilization helps prevent the loss of signals during ordinary maneuvers and during pitching and rolling caused by rough air. This stabilization is accomplished by automatically adjusting the antenna tilt so that the angle between the true vertical and the point of maximum power of the antenna beam is held approximately constant, at the value selected by the operator's manual tilt control, for all azimuths scanned and for all attitudes of the airplane attained during ordinary maneuvers. The automatic adjustment of the antenna tilt is performed by a servo system controlled by a vertical gyroscope. The servo must be capable of following fairly high rates and accelerations, and it works continuously when the aircraft is in any attitude except the normal flight attitude at which the servo is "zeroed." These requirements generally cause the servo to be rather heavy.

If high accuracy of presentation is desired for all attitudes of the aircraft, an azimuth correction of the data must be employed, since the tilt axis is generally not horizontal. In some bombing applications, high accuracy of presentation is required only at azimuths near the heading of the aircraft. Such accuracy may be obtained electronically by shifting the data laterally on the face of the indicator tube by the amount $h \tan \theta$, where h is the altitude and θ is the angle of roll. For small roll angles the approximation $h\theta$ or $h \sin \theta$ may suffice. A voltage proportional to θ or $\sin \theta$ may be made available from a potentiometer or synchro on the roll axis of the gyroscope, and a fairly simple computer may be constructed for supplying a voltage proportional to $h\theta$ or $h \sin \theta$. The lateral shifting of data may be accomplished by applying this voltage to a horizontal centering coil such as is frequently used with electromagnetic cathode-ray tubes.

PLATFORM STABILIZATION

Platform stabilization serves to keep the base of the scanning system always on a horizontal plane regardless of the maneuvers of the aircraft. It is an ideal type of stabilization, since it obtains both good illumination of the surface of the ground or sea and also accurate azimuth data. It is necessary to provide a gimbal mount for the entire scanning system to keep the base of the scanner horizontal during rolling and pitching of the aircraft. Also, a great amount of space must be provided so that the scanner can perform the necessary rotations. At the close of World War II, platform stabilization had been used only in experimental bombing systems. The physical limitations of size and weight generally ruled out this type of stabilization for ASV radar systems. Platform stabilization is accomplished by means of two servo systems which independently adjust the base of the scanner to compensate for the roll and pitch of the aircraft. These servos are controlled by synchros or potentiometers on the roll and pitch axes of a vertical gyroscope. The servos are in some respects simpler than the servo required for line-of-sight stabilization, since they have to work only during the times when the attitude of the aircraft is actually changing, whereas in line-of-sight stabilization the tilt is varied as a function of azimuth angle.

The mechanical problems of platform stabilization are partially avoided by the use of *roll stabilization*, in which case the scanner base is adjusted in roll only. Such a stabilization system also partially avoids one of the difficulties of line-of-sight stabilization in that good azimuth accuracy in presentation is preserved for azimuths near the heading of the aircraft. However, when the aircraft is in a climb or dive, good illumination of the ground or sea at azimuths near the heading of the aircraft is not automatically secured; nor is the azimuth accuracy of presentation maintained at azimuths approximately at right angles to the heading.

COMPASS STABILIZATION

The chief object of compass stabilization is to prevent the smearing of signals on the indicator tube caused by changes in heading of the aircraft. If compass stabilization is not used, the map on the indicator tube rotates as the heading changes. This rotation of the map, together with the persistence of signals on the indicator tube, results in a smearing of the tube face which may cause the loss of signals until the tube face clears. The use of compass stabilization generally makes the two types of gyroscope stabilization discussed above much more effective. Also it may assist, at times, in the solution of navigational problems.

Compass stabilization is used only in systems employing PPI presentation. In airborne radars it is usually employed in such a manner that the map on the indicator tube is always presented with north at its top. This stabilization is accomplished by means of a servo system controlled by a directional gyroscope. The servo rotates the synchro normally used for transmitting azimuth data to the indicating tube in such a manner as to add the compass heading data to the normal bearing data. It is customary, when compass stabilization is employed, to cause a bright line to appear on the indicator tube at the compass bearing corresponding to the heading of the aircraft.

RANGE STABILIZATION

The purpose of range stabilization is to keep the signal from a particular object of interest always at the same position on the face of the indicator tube. This can be accomplished by an automatic continuous variation of sweep length during a homing run on the object. Aside from a specified application to *low altitude bombing* [LAB] (see Section 8.4), this type of stabilization has received little use up to the present time, but probably would be particularly useful in following a weak intermittent type of signal, such as that from Schnorkel in the presence of sea return. Once the desired signal has been detected and the range stabilization put into operation, an apparent gain in signal-to-noise and signal-to-sea-return ratios is effected upon the indicator tube, since the noise and sea-return signals occur at random, whereas the desired signal is built up on a screen of long persistence by always appearing at the same spot on the tube, even though the signal may be missed completely on some scans of the antenna.

4.1.4 Sea Return

The importance of high resolution in minimizing the effects of sea return was mentioned in Section 3.1.4. It was noted also that the resolution is inversely proportional to the pulse duration. Thus, in order to make the performance of the radar as effective as possible in the presence of sea return, the design of the radar should incorporate the narrowest beam and shortest pulse duration consistent with the attainment of the other objectives of the design, and consistent with the physical limitations of size, weight, and power consumption.

The polarization of the beam of electromagnetic waves directed from the radar antenna is also an important consideration in the sea-return problem. Experiments indicate fairly conclusively that sea return is usually worse when the electric vector is vertical than when it is horizontal. Hence, if consistent with practical problems of antenna and scanner design, horizontal polarization is preferable for ASV radars.

The antenna beamwidth, the pulse duration, the polarization, and possibly the wavelength determine the ratio of signal strength to sea return (except for effects of conditions external to the radar itself). There are, however, several electronic devices which may be incorporated in the radar receiver and indicator circuits to improve the presentation of the desired signal in the presence of sea return. These circuits automatically operate upon the receiver and video circuits so as to reject the sea return as much as possible, without too great a loss in the desired signal, before the data are presented upon the indicator tube.[4a]

4.1.5 Scan Rate

Another factor affecting the range of any radar system is the scanning rate. Maximum range is obtained if the radar beam is continuously focused on the target; but one of the functions of an ASV system is to search continuously over a large area, and it is only after a target has thus been found that the beam is pointed in one direction. Thus, it is necessary to consider carefully the scan rate to be used and the various scanner controls that are to be built into an ASV set.

The so-called scanning loss S_{db}, in decibels, is defined as

$$S_{\text{db}} = 40 \log \frac{R_0}{R_s}$$

where R_0 is the "no scan" maximum range for a certain target and R_s is the maximum range at which this target can be seen while scanning. S_{db} varies with scan rate, type of scan, beamwidth, and other factors. A typical plot of scanning loss against scan rate shows that S_{db} is 2 db or less for scan rates of 5 rpm or less and rises to 12 db for scan rates over 30 rpm.

The saturation scanning loss may be computed approximately from:

$$S_{\text{db}} = 5 \log \frac{8}{nT_i}$$

where n is the fraction of time during which the beam illuminates the target, taken over a long period, and T_i is an integration interval (in seconds) determined by the indicator screen persistence and the memory characteristics of the observer. It varies also with the amount of signal overlap that occurs on the screen, which depends on the aircraft speed, among other things. T_i is said to have a lower limit of about 8 sec.

For the type of scan usually used with microwave ASV systems, namely, a 360-degree scan at uniform angular speed, n is the ratio of the azimuth beamwidth to 360 degrees. For sector scanning through an angle θ at a uniform rate, n is the ratio of the azimuth beamwidth to θ. We now discuss several implications of the foregoing points.

For long-range ASV search, the range will be increased by a low scan rate, but the rate used must be compatible with the aircraft speed and the sweep length on the indicator tube. That is, the target must not travel an excessive amount on the screen between successive scans. For example, in a searching aircraft traveling at 300 knots and scanning at 5 looks per minute (5 rpm), the aircraft travels 1 nautical mile between successive looks. If an indicator sweep speed of 10 nautical miles per inch is used, the signals will move across the screen in discrete jumps of 2.5 mm. This is somewhat too large to take advantage of signal build-up on a high persistence screen, and a somewhat higher scan rate would seem advisable. For higher sweep speeds, a higher scan rate becomes definitely necessary, and sector scan is valuable in homing on a target because it gives many more looks per minute, thus allowing rapid course corrections.

When designing an ASV system with the difficult and important problem in mind of searching for such small objects as the Schnorkel, a satisfactory compromise must be effected between the minimization of sea return by narrowing the beam and the resulting scanning loss at the fairly high scan rates necessary. A more detailed treatment of scanning losses has been given by E. M. Purcell.[4b]

4.2 ENGINEERING CONSIDERATIONS

The principal function of an ASV set is to detect and home on all types of surface vessels at the maximum possible range, as pointed out previously. At present this principal function divides naturally into two parts; (1) long-range detection of sizable vessels and (2) necessarily short-range detection of small objects, such as the Schnorkel. A secondary, but still important function of the ASV set is to provide navigational information.

The above functions of the ASV system affect the basic design of the set, making it more complicated in circuits and controls than a simple radar mapping set. In the same way, the special ASV functions affect the engineering considerations. General airborne radar engineering problems are considered in the R. L. Technical Series,[5a] and in Section 5.1 below engineering problems as related to maintenance are discussed. This section will accordingly treat only those engineering problems that arise from the special functions of the ASV systems.

4.2.1 Set Design

In any piece of equipment designed to be airborne, weight is a vital factor, but under certain conditions, the word "vital" has to be qualified. In military bombing aircraft, the value of a mission is not measured by the total load carried, but rather in the total damage done to the enemy. Thus, in a bombing aircraft, bomb load may have to be sacrificed for an accurate bombsight, and in an ASV plane, bomb load or range may have to be sacrificed for improved ability to find enemy vessels. Since improvement in radar range means that the aircraft does not have to travel so far to search a given area, and since in general, increased weight in a radar set gives increased radar range, it may happen that a heavier radar set will allow the patrol area of a search aircraft to be increased, or alternatively will allow the patrol area to be kept the same and the bomb load increased.

Another factor that is vital in all airborne equipment is reliability. In the very long search missions undertaken by ASV planes, reliability becomes even more important, since the effectiveness of the whole mission depends on the continued operation of the radar set. Thus the ASV system must be designed for reliable operation over long periods of time, and even an increase in weight should be tolerated in order to obtain this reliability. A corollary to reliability in an ASV set is easy accessibility to fuses, tuning controls, or any part of the system that might fail and could be repaired in flight. Thus, a properly trained operator may be able to overcome a failure in the system without having to abandon the mission and return to base. (Indeed, getting home may be a serious problem in the event of radar failure.)

Since an ASV system has several functions, the number of knobs and switches to control all the functions will naturally be greater than on a simple radar mapping system. This brings up the problem of panel layout. All too often, the panel layout is determined by the whims of the man who makes the first breadboard model of a new system, thus depending only on electrical convenience. Later, various modifications may be made to facilitate production, but very seldom are the feelings of the man who will have to operate the set considered. It is seldom possible to take a poll of all prospective operators, but some thought on the part of the designer will indicate such facts as the following. (1) Controls most frequently used should be the easiest to reach. (2) Controls performing the same general function should be grouped together, in so far as possible.

Since a large part of ASV work consists of long over-water flights, careful thought must be given to navigational aids when planning what equipment the aircraft will carry. Since radar beacons are a valuable aid to navigation, all ASV sets should incorporate beacon equipment, for the additional weight is small compared with the value gained. It is essential, however, that the beacon part of the ASV set be highly reliable, for if an operator attempts to pick up a beacon and fails to do so, he may interpret this failure to mean that he is out of range of the beacon rather than that the system is not functioning properly. Thus, he may become more confused as to his position if the beacon part of the system fails than if he had never looked for beacons.

On long search missions the task of the radar operator is very arduous, for the success of the mission depends on a constant watch being kept on the scope. It is therefore important in engineering the ASV system that everything possible be done to reduce operator fatigue. Along these lines, the proper lighting of meters and dials, and the proper color of the oscilloscope fluorescent screen and filter should be considered.

4.2.2 Installation Design

Two factors of particular importance in the installation of ASV systems are the fatigue and safety of the operator and convenience of maintenance. As mentioned above, ASV operators have a difficult task to perform. The importance of giving a man a comfortable, uncramped position in which to sit is obvious as the first step in minimizing fatigue. The proper lighting of the compartment in which the ASV operator is to work is correspondingly important. A blacked out compartment or cubbyhole should be provided and it should not be necessary to use a visor on the scope continuously. The visor forces the operator to sit in just one position, often a cramped position, while looking at the scope. Also, whenever the operator looks away from the scope to rest his eyes, he loses his dark adaption (unless he happens to be on a night patrol). Finally, it is psychologically advisable to provide the operator with a window which, though normally blacked out, will permit him to look out of the plane if he so desires. This will relieve any mental stress due to a feeling of being completely closed off from all reality.

It has been found that electrical interference often causes spots not unlike signals to appear on the PPI. Presence of such interference from blowers, turrets, and generators places the operator under the continual strain of attempting to distinguish real targets from false ones produced by mechanisms within the airplane. When making a radar installation, great care should be taken to minimize such interference.

Since ASV aircraft make attacks from a relatively low altitude, and therefore, because of enemy action, may have to ditch on very short notice, everything possible should be done in making the installation so that the operator may quickly get into a safe ditching position. That is, an area of the forward bulkhead of the ASV compartment should be left clear and this area should be easy to reach. Thus, in an emergency, the operator can quickly get into a position with his back against the bulkhead. Perhaps the best solution of this problem is to place the operator's chair and a headrest against the forward bulkhead.

4.2.3 A Typical System, AN/APS-30

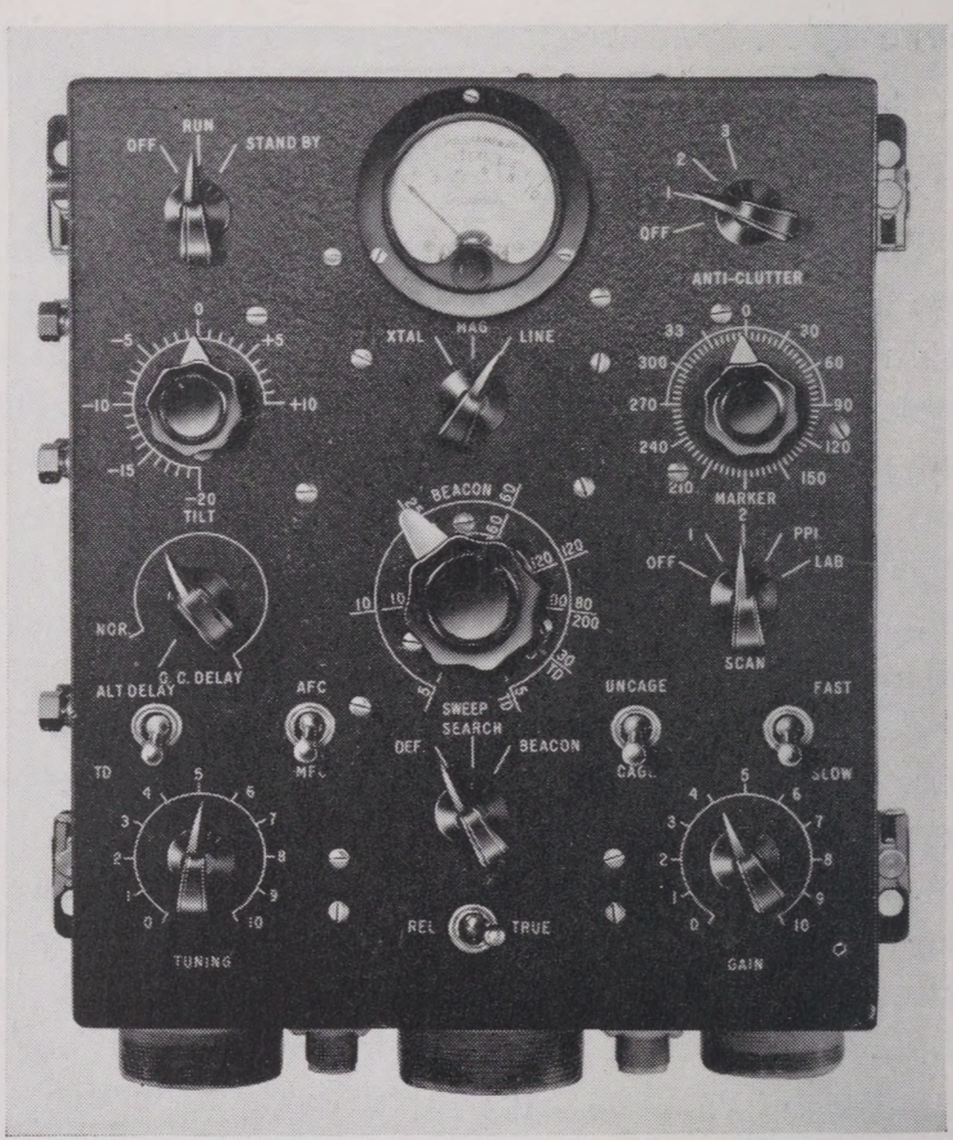


FIGURE 1A. Control unit (AN/APS–30).

One of the last ASV systems designed during World War II and therefore incorporating most of the recent improvements is the AN/APS-30 series. The series consists of four systems with modulator, indicators, synchronizer, stabilization equipment, and cabling common to all. Two of the systems, the AN/APS-32 and the AN/APS-34, were designed primarily for bombing, resolution being stressed at the expense of range; they will not be further discussed here. The other two systems are the AN/APS-

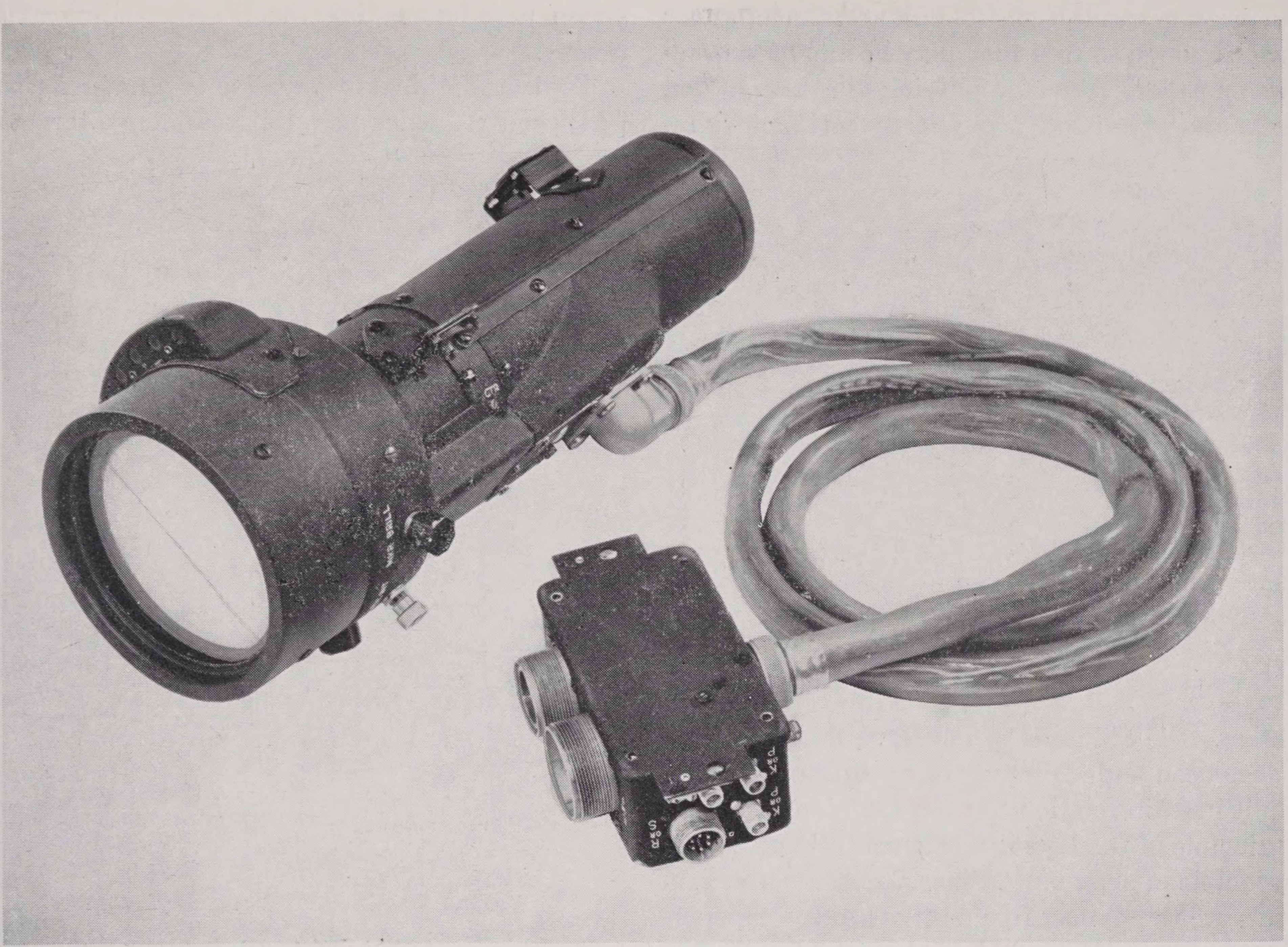


FIGURE 1B. Plan position indicator (AN/APS-30).

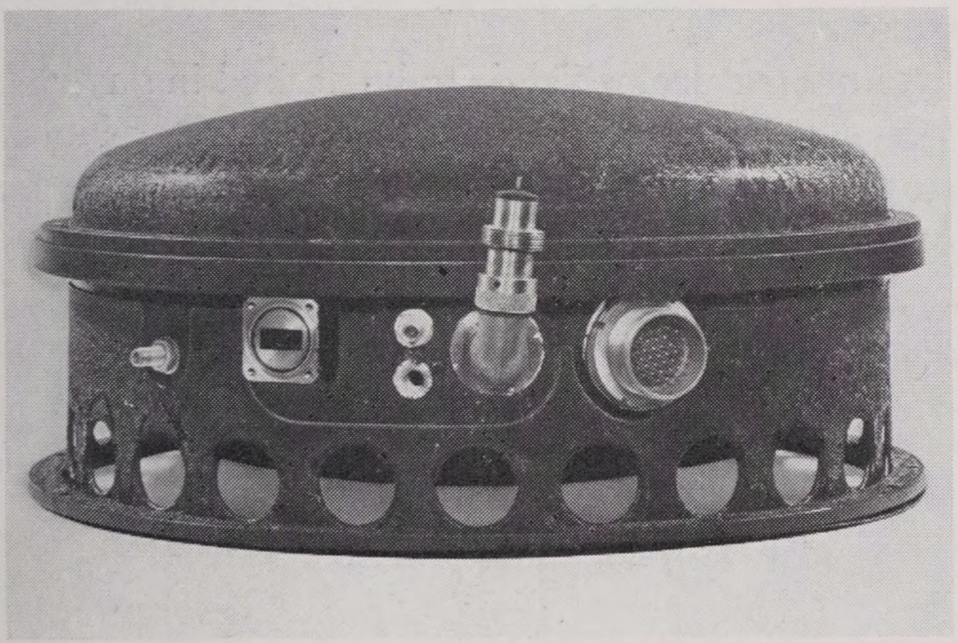


FIGURE 2A. R–F head (AN/APS-30).

31 and the AN/APS-33. The AN/APS-31 has a small antenna which scans only through 150 degrees in the forward direction, while the AN/APS-33 has an antenna with a 29-in. aperture scanning through 360 degrees. The major components of the latter system are shown in the accompanying photographs (see Figures 1, 2, 3, 4). The components for the AN/APS-31 are identical except for the scanner assembly.

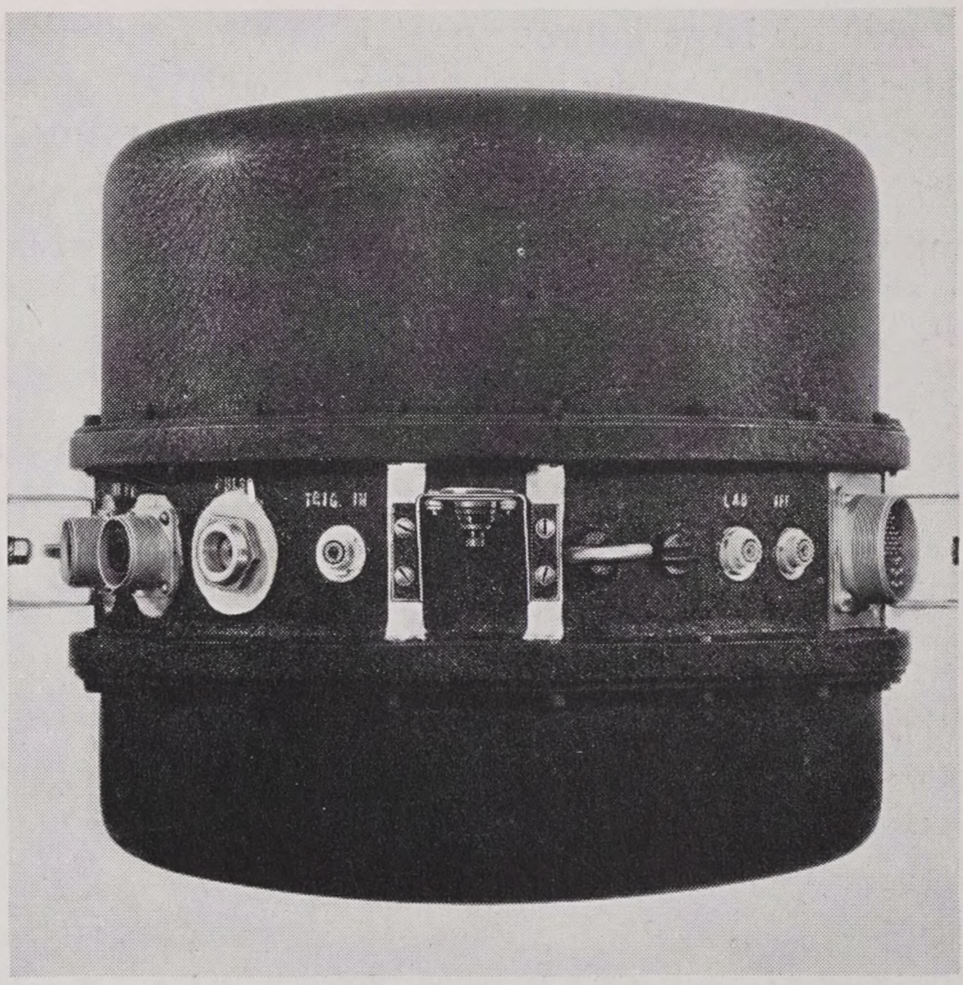


FIGURE 2B. Modulator (AN/APS-30).

The series incorporates several improvements over previous systems. All the controls have been grouped in one position and the control unit and the indicator are small enough so that they may be mounted practically anywhere, thus simplifying the installation problem and permitting a physically satisfactory installation. It is of interest to observe that, although there has been some grouping of controls on the control unit itself in relation to their functions, the general principle of the layout of the control unit is still the principle of symmetry. Since the sweep and gain controls are those most frequently used by the operator, undoubtedly it would have been better to have the sweep control in the lower left-hand corner, which is a position easier to reach than the center of the box.

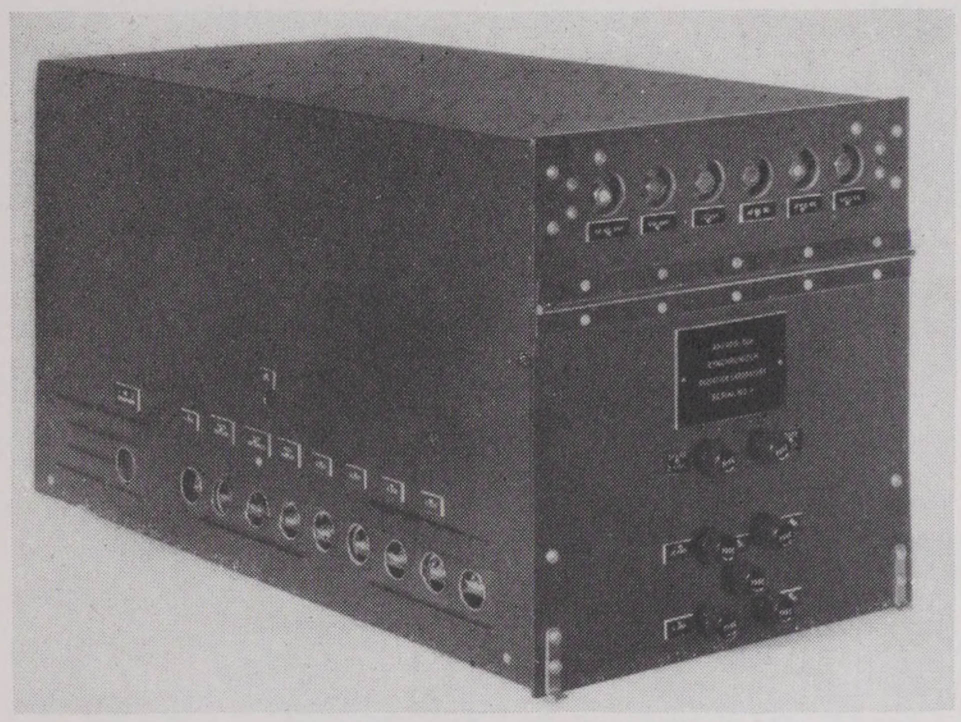


FIGURE 3. Synchronizer (AN/APS-30).

Another large improvement is in the beacon features that the system incorporates. Beacon automatic frequency control, a wide band *intermediate frequency* [i-f] amplifier, and video stretching all combine to improve beacon performance greatly. A delayed fast sweep permits reading the beacon coding at long ranges.

Typical ASV features are the *target discrimination* [TD] control which permits examining a target on a fast sweep while it is still at long range, thus aiding differentiation between clouds and more solid targets, and the provision of a 5-μsec pulse on long-range sweeps.

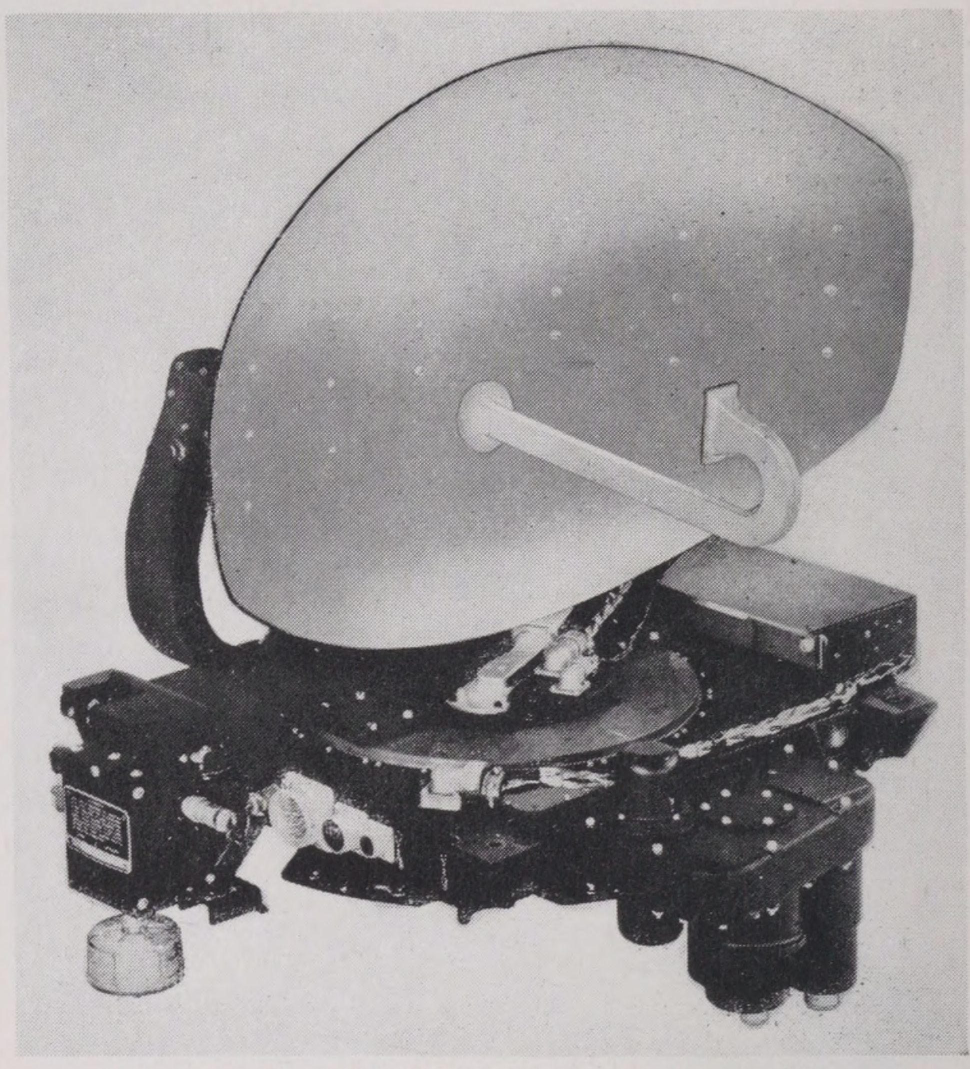


FIGURE 4. AN/APS-33 scanner assembly.

A final feature, which is to be desired in any radar system, is the hermetically sealed r-f head and modulator, which includes the indicator high-voltage supply.

Chapter 5

ASV PERFORMANCE

The three foregoing chapters have considered the functions of, means of detection by, and design considerations for *aircraft to surface vessel* [ASV] radar systems. It is now desirable to examine the performance which can be obtained with an ASV radar system, with particular reference to the various factors affecting that performance. In general three major factors determine the performance of an ASV system. The first, radar maintenance, is directed at attaining and maintaining the peak performance for which the particular ASV system was designed; this is analogous to maintenance of the aircraft motors to insure optimum performance. The second factor, range performance, is associated with the operational features influencing maximum range, such as horizon limitations on range, and the significance of scanning rates and the observed persistence of targets on the indicator screen. The third factor, operational methods, involves the relationship between tactics and performance, and includes operator fatigue, methods of patrol and attack, and target identification (as friend or foe). These three groups of factors are discussed in the three sections that follow. Although this discussion pertains to ASV performance, certain of the concepts are directly and equally applicable to the performance of other radar systems discussed in subsequent chapters. This is particularly true of the section on radar maintenance. Sections 7.4 and 15.2.2 are an extension of the application of these notions to bombing and *aircraft interception* [AI] radar systems respectively (essentially similar extensions can be applied to *airborne gun laying* [AGL] and *airborne moving target indication* [AMTI] systems discussed in Parts IV and V).

5.1 RADAR MAINTENANCE

5.1.1 Introduction

The function of radar maintenance is to attain and maintain peak performance of the radar system. When two different radar sets are compared on the basis of the operational ranges obtainable with each, the set with the greater range is said to have the higher performance. This type of performance, called *range performance*, depends upon the design characteristics of the radar system including such features as the gain of the antenna, scanning rates and scanning losses, antenna beamwidth, the type of indication, the peak power output of the transmitter, and the sensitivity of the receiver.

The concept of performance used in radar maintenance is called *radar performance*. This concept differs from the usual concept of range performance. Its definition and some general considerations concerning it are given in Section 5.1.2. Other aspects of radar maintenance, namely, maintenance policy, design considerations, instruction literature, maintenance training, and special radar test equipment are presented in Sections 5.1.3 to 5.1.7.

5.1.2 General Considerations

Radar performance is defined as *the ratio of the peak power output of the transmitter to the weakest signal power which the receiver can detect*: $P/p_{\min}$. This definition is modified somewhat for the purpose of tests and measurements in that the signal power used is a test signal power, p_T. Hence, the definition of radar performance (for maintenance purposes) becomes P/p_T.

Usually p_T is selected as one of the following three quantities: (1) the minimum discernible test signal power, which may be the same as the minimum discernible signal power; (2) the tangential test signal; and (3) the *continuous wave* [CW] test signal power equal to the noise signal power. A minimum discernible test signal is an amplitude-modulated (pulsed) or frequency-modulated signal which is attenuated (through attenuators in the test set) until it is barely discernible in the receiver noise. A tangential test signal is an amplitude- or frequency-modulated signal which is attenuated until the bottom of the noise on the signal pattern is of the same height as the top of the noise without the signal. A CW test signal is attenuated until the voltage developed across the second detector (as measured with a meter) indicates a power equal to the noise power (as measured with a meter in the absence of signal).

The ratio P/p_T, expressed in decibels, is called the *radar performance figure*, and is a measure of the ability of the radar system to detect targets with a given set of external conditions. Assuming constant external conditions, for example a target in free space, it is possible to correlate changes in range with changes in radar performance by using the inverse fourth power law. Since the power of a returning signal is always proportional to the power in the transmitted pulse this law may be written

$$R = K\left(\frac{P}{p_R}\right)^{\frac{1}{4}}$$

where p_R is the power received from a target at range R, P is the peak transmitted power, and K is a constant depending upon the characteristics of the target and design factors of the radar system [see equation (1) of Chapter 7 and equation (3) of Chapter 15]. For beacon reception the inverse square power law obtains, namely,

$$R = K(P/p_T)^{\frac{1}{2}}.$$

If the relative value of range is plotted in per cent against the decrease in radar performance figure, a graph such as that shown in Figure 1 is obtained.

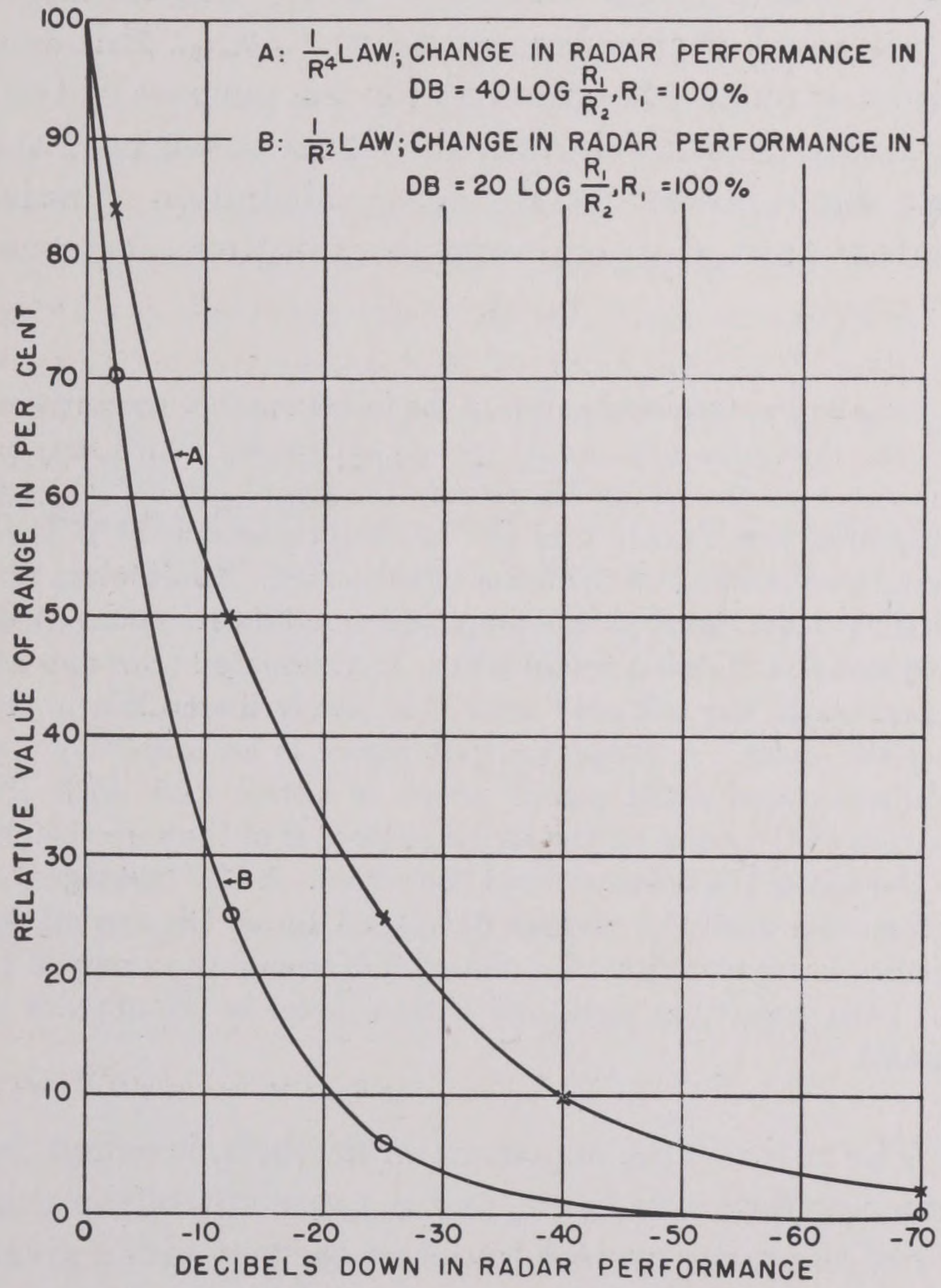


FIGURE 1. Radar performance in decibels as a function of range. A = radar curve, B = beacon curve.

A priori, the range performance of a radar system is judged on the basis of the maximum range obtainable with it. This, of course, is necessary for operational comparisons. However, it is not possible to measure radar performance accurately by observation of the maximum range, since in general, complete information on the external factors affecting range is not available. The external factors which affect range are: (1) the reflection properties of the target; (2) differences in path length between reflected rays, which may cause the rays to reinforce or to cancel; and (3) atmospheric conditions, such as temperature and humidity effects which may cause the radar beam to be bent upward, thus rapidly dissipating the energy in the beam, or downward, thereby delaying the dissipation of the energy. A change in any one of these conditions is reflected as an apparent change in radar performance, which may be favorable or unfavorable — an apparent increase or decrease in performance. Consequently, in judging the performance of a radar system, it is unwise to use the signal returned from a given target selected as a standard. Rather, the radar performance figure should be measured by use of the appropriate test equipment.

The internal factors (those within the radar set) which influence radar performance are of two kinds: those affecting peak transmitter output power and those affecting the minimum discernible signal. The peak power output of the transmitter is dependent upon the following: (1) the quality of the transmitter tube (spectrum and tube efficiency); (2) the magnetic field strength (if a magnet is used in conjunction with the transmitter tube such as with magnetrons); (3) the pulse peak voltage applied to the transmitter tube; (4) the shape of the pulse voltage applied to the transmitter tube; (5) losses or mismatch in the transmission line, caused by a detuned TR or foreign material or discontinuities in the line; (6) a nonfiring TR or ATR; and (7) losses in the rotating joint or antenna connections. In practice, the average power output of the transmitter is measured and correlated with the peak power output by the relation

$$P_{\text{avg}} = P \cdot \tau \cdot \nu_r,$$

where P_{avg} is the average power output of the transmitter, τ is the pulse duration, and ν_r is the pulse recurrence frequency. Thus, the pulse duration and the pulse recurrence frequency have to be known in order to determine peak power output accurately.

The receiver performance figure, 10 log p_T, which is a measure of the ability of the receiver to detect a weak signal as determined by a test signal p_T is dependent upon the following: (1) quality of the crystal (gain and noise); (2) local oscillator tuning; (3) *automatic frequency control* [AFC] performance; (4) TR and ATR tuning, and losses through each of these; (5) noise of local oscillator; (6) noise of the i-f amplifier; (7) transmission line losses; and (8) the factors which determine how far into noise a signal can be seen, namely, i-f bandwidth, video bandwidth, pulse recurrence frequency, sweep speed, spot size, and type of presentation (if an oscilloscope is used, as is generally the case in making receiver sensitivity measurements).

Receiver sensitivity is best measured in terms of noise figure, which is accurately defined but somewhat difficult to measure, especially under field conditions.

Noise figure is the ratio of the available noise power from all sources within the actual receiver including the antenna (referred to the input terminals) to the available noise power from the antenna alone ($k^\circ TB$ where k° is Boltzmann's constant, T is the absolute temperature, and B is the i-f bandwidth). Noise figure is usually expressed in decibels and is equal to unity for an ideal receiver. The test signal power p_T in decibels is related to the noise figure as follows.

$$10 \log p_T = 10 \log k^\circ KB - N_r + C,$$

where N_r is the overall receiver noise figure and C is a constant depending upon the i-f bandwidth, the video bandwidth, the pulse recurrence frequency ν_r, the sweep speed, spot size on the indicator, and type of presentation. C is determined empirically; it is negative for a minimum discernible test signal (approximately 4 to 8 db below the signal whose power is just equal to the noise power); and positive for a tangential test signal (of the order of 6 to 10 db above the signal whose power is just equal to the noise power).

In practice the value obtained for the test signal power is taken as a measure of the receiver sensitivity; the precise value to be attained is prescribed for the particular system on which the measurement is made, and for the type of test signal employed. A check on the i-f bandwidth can be made with an amplitude or frequency modulated test signal.

Since the radar performance figure is determined by the peak power output of the transmitter and the sensitivity of the receiver, each of these quantities should be measured and the radar performance figure computed. The adequacy of performance is determined by comparing the value obtained in this way with the prescribed value for the radar performance figure. Some of the factors affecting the peak power output of the transmitter and the sensitivity of the receiver are not easy to check in the aircraft. Therefore, in the process of maintaining the peak performance of the radar system, it is necessary to specify the factors which are to be checked in order to determine the radar performance figure and guarantee peak performance; where the various factors are to be measured, for example whether at the aircraft or on the bench; and the relative frequency with which the measurements are to be made. In order to insure rapid maintenance with the greatest efficiency, a specific maintenance procedure (maintenance policy) should be adopted and pursued. The basic considerations involved in such a policy are presented below. Of course, the evolution of various types of radar systems, improvements of engineering design, and installations in new types of aircraft will necessitate a modification of these considerations.

5.1.3 Maintenance Policy

A maintenance policy that proved useful and suitable during World War II was based upon the following practices: (1) making a brief series of quick, simple, routine tests at the aircraft to check the performance of the system before each flight, (2) making a series of simple tests at the aircraft to localize a faulty major assembly so that the faulty assembly can be replaced; and (3) making a series of tests on the bench for the isolation of a faulty subassembly or functional unit in a major assembly, so that it may be replaced and subsequently repaired.

When a maintenance policy of this kind is adopted, two facts have to be known: (1) the parameters which have to be measured in each of the above three categories have to be specified; and (2) terminals (called test points) for connecting the test equipment to the radar system have to be provided. The parameters can be grouped conveniently into two classes: those necessary for making routine measurements and for isolating one faulty major assembly from another; and those necessary for isolating one faulty subassembly or functional unit from another. Correspondingly, the test points can be classified as external test points — those essential for making the first and second categories of measurement; and internal test points — those essential for making the third category of measurements. Since the inclusion of test points in a radar system affects the design of the system, test points are discussed somewhat more fully under the subject of design considerations (see Section 5.1.4).

The parameters to be checked in making routine measurements were arbitrarily designated primary parameters; those for isolating one faulty major assembly from another, secondary parameters; and those for isolating one faulty subassembly or functional unit from another, tertiary parameters. Some of the primary parameters that were used are (1) receiver sensitivity, on search and beacon; (2) transmitter power output, on search and beacon; (3) AFC operation;

(4) TR recovery (primarily for systems requiring close-in performance); (5) transmitter tube and crystal currents; and (6) transmitter spectrum. Some of the secondary parameters measured were (1) ground continuity between all major assemblies, open circuits from ground, and continuity of all cable leads; (2) d-c and a-c voltages; (3) sweep voltages; (4) choke-flange joints in the wave guide for secure fits. Some of the tertiary parameters included filament voltages, critical voltages and waveforms, critical currents, and AFC and local oscillator adjustments.

5.1.4 Design Considerations

Execution of the above maintenance policy imposes specific requirements on the design of the radar system. The light weight and small size of the equipment is fundamental for aircraft radar systems. The design has to be such that the system as a whole is comprised of individual major assemblies which can be readily isolated one from another in the event that one is faulty; and such that each major assembly is comprised of individual subassemblies (in so far as practicable), which also can be readily isolated one from another in the event that one is faulty. A judicious compromise should be effected between the requirements for ease of maintenance (sufficiency and accessibility of test points) and the necessity for light weight and stowage in remote corners of an aircraft.

Test points are designed into the radar system. External test points for measuring the primary parameters are located on a readily accessible test panel. External test points for isolating one faulty major assembly from another are on the major assembly proper and are designed for accessibility when the equipment is installed. Internal test points, for isolating faulty subassemblies or functional units, should be located on a terminal board used as a test panel, or in some cases on the subassemblies or functional units themselves.

Essential external test points are: (1) directional coupler output, (2) trigger output, (3) test video (including range marks), (4) d-c and a-c input voltages, (5) scanner on-off switch, and (6) critical voltages and waveforms (should be limited in number). Essential internal test points are: (1) a-c and d-c voltages, (2) currents (including crystals and transmitter tube currents), (3) impedances, and (4) points for examining critical waveforms, including range marks.

Test points should have certain characteristics, including ready accessibility, appropriate and clear labels, standard connectors or fittings, and presentation of the system parameter to be tested in an appropriate form (with regard to voltage and power level) for use with the available test equipment. Recommendations as to the characteristics of these various test points have been made by the Joint Radio Board and are contained in its reports.[8–10]

The most important external test point is the output of the directional coupler, for without this test point it is not possible to make simple, reliable, quantitative measurements of the fundamental quantities in determining radar performance, power output, and receiver sensitivity.

A directional coupler is a device by which a known fraction of r-f energy is coupled out of the main transmission line (wave guide or coaxial) to a power meter, a frequency meter, an echo box, a signal generator test set, or a spectrum analyzer; and by which this same known fraction of energy is coupled back into the transmission line from the echo box or from the signal generator test set. A directional coupler consists of a short section of transmission line (usually part of the main line) and an attached section of secondary line (called the auxiliary line). One or more openings (holes or slots) couple energy from the main line into the auxiliary line which is then coupled out through a matched probe to the test point, which may be a coaxial fitting or a wave guide fitting. Some couplers are unidirectional, coupling energy from the transmission line from one direction only; others are bidirectional, coupling energy from the transmission line from either direction. The desirable characteristics of a suitably designed directional coupler are contained in reports[8–10] of the Joint Radio Board.

A pick-up antenna (horn or dipole) placed in front of the radar system antenna provides for connecting the radar system to the test equipment, such as the signal generator test set, power meter, echo box, or frequency meter. It is only by use of a pick-up antenna that a check on the entire radar system, including the antenna, can be made. Unless the coupling loss between the system antenna and the pick-up antenna is accurately known, precise measurements cannot be made. There are some systems for which it is desirable to use a pick-up antenna for alignment procedures, such as for boresighting (alignment of the axes of the guns and the radar system antenna) or antenna alignment in general, in which case it is not necessary to know the magnitude of the coupling between the two antennas. Hence, an additional aspect of radar system design (from the point of view of radar maintenance) becomes important, namely, ease in removing the radome. Thus, access to the scanner is provided, for possible adjustment or repair.

The design of the radar system may be influenced also by the inclusion of special test accessories, such as built-in test oscilloscopes for some long-range navigational systems or a calibrated movable range mark for echo box measurements.

5.1.5 Instruction Manuals and Maintenance Training

Once the maintenance policy has been established and the radar system designed in accordance with the tenets of such a policy, literature for maintenance personnel should be prepared. During World War II this literature took the form of instruction manuals, called "Handbooks of Operating and Maintenance Instructions." These handbooks usually described the entire radar system with a separate section on the maintenance of that system. The sections on maintenance in the handbooks which appeared during the early part of the war were often not very complete, because of the state of radar development and the inherent lag between system and test equipment design and production. However, the handbooks prepared toward the close of World War II were very comprehensive indeed.

The following is a list of the features included in the section on maintenance in one of the recent handbooks: (1) the precise maintenance procedure to be followed; (2) a complete description of and operational procedures for the use of each item of test equipment, including all the requisite calibration data; (3) the rated and minimum acceptable values for the various parameters; (4) a list for and relative frequency of routine inspections, such as daily inspection, 100-hour inspection, and 500-hour inspection; (5) removal, disassembly, and servicing of various units; (6) alignment procedures for the radar system; (7) complete circuit diagrams for the radar system (major assemblies and subassemblies) and for the test equipment to be used with it; (8) a trouble-shooting chart for the isolation of one faulty major assembly from another; (9) a trouble-shooting chart for isolation of one faulty subassembly or functional unit from another; (10) a trouble-shooting chart for the localization of r-f troubles; (11) a trouble-shooting chart for localizing troubles in faulty subassemblies; (12) a complete list of voltages, currents, impedances, and waveforms to be expected with the precise method of measurement given; (13) a list of the functions of each major assembly; (14) a list of the tube complement and function; and (15) a list of emergency repairs, which might be made in flight.

Adequately trained maintenance personnel are essential to the attaining and maintaining of peak radar performance with the greatest efficiency. Although this statement is self-evident, the problems associated with a suitable training program are very extensive indeed. A detailed discussion of these problems is presented in Section 13.2.3.

5.1.6 Radar Test Equipment

The rather amazing development and applications of radar systems during World War II was accompanied by an equally amazing development of test equipment for radar systems. Since the radar performance figure can be determined accurately only by use of appropriate test equipment, it is of interest to note some of the items of test equipment that were developed during the war for use with radar systems. The following is a list of a few such items, with their essential functions. Detailed listing of particular test equipment items for individual radar systems is contained in the recommendations of the Joint Radio Board[8]; descriptions and properties of the items detailed in the Joint Radio Board recommendations (and for other test equipment items) are presented in the U. S. Radar Survey.[1]

1. *Echo Box.* Provides a quick, rough measure of the overall radar performance. It measures frequency, relative power (roughly), and spectrum width; detects double moding of transmitters and checks on AFC operations. The echo box is not suitable for beacon receiver sensitivity checks.
2. *Power Meter.* Measures the average power of radar transmitters, and of CW or modulated signal generators. It can be used in conjunction with an echo box to localize poor overall radar performance in the transmitter or in the receiver.
3. *Frequency Meter.* Measures the frequency of radar transmitters, CW or modulated signal generators, and beating oscillators; detects double moding; and in some cases contains provisions for viewing the pulse or wave shape. In general, it is not essential to measure radar transmitter frequency; also the output of certain local oscillators is inaccessible. The most useful application is for checking signal generator output at beacon frequency; consequently, considerable absolute accuracy is required (± 0.5 mc).
4. *The Signal Generator Test Set.* Measures average transmitter power on search and beacon; receiver sensitivity on search and beacon; checks AFC operation and local oscillator adjustments; measures transmitter frequency, spectrum width (if the Q of the frequency meter is sufficiently high); checks TR and ATR tuning, TR recovery, and nonfiring TR's and ATR's.
5. *Crystal Checker.* Measures front resistance, back resistance, and back crystal current at 1 volt. On the basis of these measurements good crystals can be selected from poor ones.
6. *Radio-Frequency Load.* Provides an r-f test load of good match, into which the transmitter can operate.
7. *Standing Wave Device.* Measures voltage standing wave ratio of r-f components in wave guide and transmission lines and is particularly useful for very high frequency radar transmitters which are frequency sensitive to the matching load into which they operate.
8. *Spectrum Analyzer.* Displays a picture of all frequencies, within a given band radiated by the transmitter and local oscillator; measures pulse duration, spectrum width, and the Q of resonant cavities, and checks the frequency of signal generators, local oscillators, transmitters, TR and ATR boxes.
9. *Power Absorption Cone or Screen.* Absorbs power from the antenna (to prevent reflections from nearby objects and interference with nearby systems).

5.1.7 Conclusion

The significance of radar maintenance in ASV performance has been discussed above in some detail both because the subject is important and because the concepts involved differ somewhat from many of those discussed in other parts of this book. It is of value to reiterate the earlier statement that although this section on radar maintenance was written primarily with reference to ASV performance, the concepts involved are immediately applicable to other types of radar systems, with modifications and extensions in accordance with the requirements of the particular system.

5.2 RANGE PERFORMANCE OF A TYPICAL SYSTEM

One of the most important characteristics of any ASV radar is its maximum range. Many factors affect the range of a radar set.[4c] One limiting factor that a microwave radar set cannot overcome is the horizon.

5.2.1 Horizon Limitations

In Table 1, the horizon range is given for several heights of the radar antenna and the reflecting object. Various cases of anomalous propagation have been observed on ground-based or shipborne radars,[2a] but airborne radars have not given a greater than horizon range, except for the very slight increase in range due to refraction of the radar beam in the atmosphere. Thus, Table 1 shows the maximum range that may be expected from a microwave radar set under the conditions shown.

TABLE 1. Approximate horizon range in nautical miles for various target and radar heights.

Height of radar in feet	Height of target in feet 5	10	20	30	50
100	15.1	16.2	17.8	19.0	21.0
300	25.9	27.0	28.6	29.9	31.2
500	30.3	31.4	33.0	34.2	36.2
1,000	41.6	42.7	44.3	45.5	47.5
3,000	70.1	71.2	72.8	74.0	76.0
5,000	89.7	90.8	92.4	93.6	95.6
10,000	102.8	103.9	105.5	106.7	108.7
30,000	215.8	216.9	218.5	219.7	221.7
50,000	277.8	278.9	280.5	281.7	283.7

From Table 1 it will be seen that even for an aircraft at 10,000 ft, the horizon range is still less than 150 miles. With present beacon techniques, reception at 150 or even 200 miles is not exceptional. Therefore, since ASV search missions are seldom carried out at altitudes greater than 10,000 ft, it is safe to say that beacon reception will only be limited by the horizon. The same cannot be said for radar ranges.

5.2.2 Typical Values

Before mentioning the maximum ranges that may be expected with certain ASV systems on various-sized ships, it is necessary to define what is meant by the maximum range of a radar set. Since it is customary for an ASV system to scan at a rate sufficiently slow so that the eye can easily resolve the separate scans, the observer will notice that as the range to a target increases, the signal decreases in intensity; but before the intensity is so low that the signal is indistinguishable from noise, he will note that although the signal may have fairly high intensity on a certain scan, it will not appear at all on the subsequent scan. As the range continues to increase, the percentage of scans in which the target is visible will continue to decrease until the operator may feel fairly certain, but still cannot be positive, that the target will not appear on the next scan. At such a point, the radar system could be considered to have reached its maximum range on the target in question. On the other hand, it is the purpose of an ASV system to search the entire area about the plane that carries the system. An operator can hardly be expected to notice every signal that appears on the PPI every scan. Thus, if the range to a certain target is so great that the signal appears only once every six scans, it is very possible that the operator will completely overlook that target. Since it now becomes evident that the useful maximum range of an ASV system depends to a large extent on the vigilance of the operator, it is necessary to be somewhat arbitrary in defining maximum range. Therefore, the term maximum range as used in this section will mean the range at which the target is visible on 50 per cent of the scans.

Although with the older ASG systems such as the SCR-517 or the ASG a range of 50 or 60 miles on a large battleship would be considered good, a recently designed system such as the AN/APS-33 is capable of horizon range on the same type of ship unless the ASV system is above 10,000 ft. Cruisers or large freighters give a maximum range of 60 to 70 miles on the AN/APS-33, whereas destroyers and smaller freighters give ranges of 40 to 50 miles.

Submarines will give a maximum range of approximately 30 miles when riding high in the water, but when running partially submerged, or completely submerged with only a periscope or a Schnorkel tube above the surface, the maximum range is greatly reduced. Under such conditions, special means (see Section 3.2.3) must be resorted to in order to obtain any reasonable sort of range. A system designed particularly for detecting submarines operating with only a Schnorkel tube exposed, the AN/APS-15BM, incorporating a short pulse (1/4 μsec), narrow beam (1.4 degrees), and the latest anti-sea-return circuits, showed a maximum range of 14 miles on a Schnorkel. Systems less specially designed have ranges of 8 to 10 miles on a Schnorkel.

5.3 OPERATIONAL METHODS

5.3.1 Fatigue

The task of watching a scope hour after hour is a very difficult one, and many of the ASV aircraft used during the war were capable of patrolling for 18 hours or more. Tests indicate that a period of ½ to 1 hour is as long as a man can operate an ASV system and still maintain high efficiency. Eyestrain is particularly bad in the case of a PPI, where the operator must follow the rotating trace with his eyes in order to have the best chance of seeing weak signals.

Fatigue can be moderated in four-engined aircraft, which normally carry a crew of nine to twelve men, by rotating watches. In the RAF four men were trained so that they could trade shifts at the radar, the radio, and the guns. Twin-engined aircraft normally have a large enough crew so at least two men can switch positions hourly. Single-engined planes of the TBM type present more difficulty in alternating positions, and indeed in some planes of this general class positions cannot be changed in flight. However, most of the search radar equipments built during World War II were equipped with at least two indicators, and the auxiliary indicator can be installed so that another crew member may relieve the radar operator without changing positions. The burden of keeping the radar in proper adjustment is still left to the radar operator in this type of installation.

Since watching a PPI is a particularly tiring task, some work has been done on circuits which are designed to flash a light or provide an audible tone when a target appears between previously set range limits (alarm circuits). A really good alarm system would be of very great help to an operator by supplementing his watch of the tube.

Early radars of the lobe-switching type employed a double A scope for indication (see Section 3.1.2). This type of indication does not require the operator to move his eyes as does the PPI. Operators report that this is a very big advantage on long patrols. Possibly some such type of indication could be employed on microwave radars as an auxiliary to the PPI. An A scope employing a tube with a persistent screen, with the signals intensity-modulating (as well as deflecting) the electron beam, is worth investigating as a means of relieving operator eyestrain.

5.3.2 Patrol Methods

Three general types of operations were carried on during the war by ASV planes: patrol sweeps over large areas such as the Bay of Biscay, convoy escort, and the hound-to-death search of a small area. Each of these has special problems associated with it.

The sweep of an area is the most straightforward type of search. Here a group of planes are sent out to fly parallel paths through an area, usually returning through the area on another set of parallel courses. The principal problem is that of navigation, insuring that all parts of the area are covered without a large amount of overlapping. The number of planes to search an area completely is, of course, inversely proportional to the dependable range of the radar system employed. A radar system which gives maximum ranges of 30 miles broadside and 15 miles end-on for a submarine, taking into consideration the possible distribution of aspects and other factors, gives a swept path (a path width in which all submarines would be seen) of about 12 miles. To sweep an area such as the Bay of Biscay which contains about 150,000 square miles requires a considerable number of airplanes employing the best of the microwave radar developed during the war.

Increasing the range of the radar does not gain *operationally* all that one might expect. Targets picked up on the radar must be investigated. Good *identification of friend or foe* [IFF] would eliminate the need for investigating friendly vessels. However, with present radar systems, a great many targets turn out to be such things as whales, porpoises, and floating debris. If targets are sighted at long range, the patrolling aircraft must depart a long way from its course to investigate them. Thus, there will be some optimum system performance for a particular area, considering that increased performance is generally obtained at the cost of increased weight and increased drag. In an area where there are relatively few targets other than those sought, a long-range system will be useful. In a relatively congested area, little would be gained by going to higher-powered systems.

Many planes were lost during World War II because of errors in navigation. Flying 8 or 9 hours out to sea and back again with deviations from the patrol course to investigate targets puts a heavy burden on the navigator. Loran becomes of great value under these conditions.

Long-range planes, operating from Newfoundland, Iceland, and Northern Ireland were called upon to do much convoy work reaching out into mid-Atlantic. One of the major problems here was that of locating the convoy especially in bad weather. A long-range microwave radar set was a great help, although pilots frequently flew too low to get maximum ranges. Microwave beacons carried by one of the escort vessels, or Loran, would have been valuable aids.

Once the convoy was located, the planes circled it hour after hour, always on the lookout for submarines. In the early days of the war, when escort vessels were scarce, the escorts did not dare leave the convoy to attack a submarine for fear another would slip in while they were gone. The submarines would attempt to slip by the convoy on the surface during the day in order to lie in wait ahead of them at night. The escort planes did a very good job of keeping the submarines submerged, and since the submarines' underwater speed was less than that of the convoy, they could be left behind.

Planes flying from escort carriers and equipped with radar did a most effective job in convoy protection. Some of these planes were also equipped for night operation. The principal weakness remaining in the defense was the difficulty of flying from small carriers in rough seas and poor visibility conditions. Land-based planes also frequently failed to make an appearance because their bases were closed in by weather. Extension of all-weather flying techniques would relieve this situation.

The hound-to-death tactics could be made very effective. These tactics are employed once a submarine has been detected but not killed. The submarine skipper, when detected, has very few choices of tactics to be employed. He can sit on the bottom, if the water is shallow, and wait for possibly 60 hours, or can decide to proceed at the most economical underwater speed for maximum range. (The German submarines could cover about 40 miles at a speed of 2 knots.) Thus, after a contact and a dive, the area in which the submarine can be is initially very small, expanding slowly until the radius is 40 miles. If the submarine is sighted when it surfaces after a prolonged submergence and is forced to dive again at once, then its defensive measures are almost exhausted. A sufficiently intensive search in the area is bound to result in a kill.

One of the biggest difficulties in employing these tactics is getting an accurate fix at the time of sighting. Loran would of course help here. Another possible approach would be to have the sighting craft, plane or surface vessel, drop a floating microwave beacon. This could be homed on either by plane or surface vessel. Sono buoys dropped by the aircraft could also be a big help. During the war, submarines frequently made their escape because of the extreme difficulty of keeping the search area fixed, particularly under poor visibility conditions. Extension of navigation and marking techniques and improvements in all-weather flying abilities will help.

During the closing days of the European operations of World War II, the Schnorkel[7] made its appearance. Some Schnorkel installations included very effective radar camouflage. This presented a difficult problem which was never satisfactorily solved. The maximum range on such an object was small, particularly in a rough sea. Also the problem of seeing it through sea return was great. The attack initiated and to be followed in attempting to solve this problem includes the following points.

1. Increase in maximum range by improving radar system performance.
2. Improvement in signal-to-sea-return ratio by shorter pulses, by narrower antenna beams, and by circuits to suppress sea return.

5.3.3 Methods of Attack

The most common type of attack made by aircraft against submarines was a daytime, depth-charge attack. Depth charges were released from a very low altitude of about 30 to 50 ft. These were released in a string. A string of six 250-pounders was frequently used with 100-ft spacing. The release was usually made by the pilot without benefit of bombsight. The most desirable attack was a quartering attack. Since a submarine is noisy when running on the surface, a plane cannot be heard at any great distance from the deck. Some pilots were able to take advantage of this in making a down-sun approach in order to strike with very little warning. With planes which carried sufficient depth charges, this sometimes permitted a second run.

A German submarine required about 40 sec to crash dive. If the submarine crew spotted the plane when it was several miles off, they could dive sufficiently rapidly to get away. On the other hand, a skillful aircraft crew could keep the submarine in sight with the radar without being seen from the submarine, get on a course to give a down-sun approach, or in some cases, climb into the overcast, and thus increase their chances of making an undetected approach. It will be seen that such an approach requires the closest cooperation between pilot, radar operator, and navigator, thus emphasizing the importance of continuous training of the whole crew (see Section 13.2.3).

Many night attacks were made by using searchlights on the aircraft. These lights were fitted with controls so that they could be steered by a crew member. When a target was picked up by the radar, the aircraft started on a homing course without change of altitude until the range to target was reduced to about 5 miles. At this point altitude was rapidly reduced to 500 ft or less in order to avoid losing the target. The approach was continued until the plane was about three-quarters of a mile away and the light was then switched on. An attempt was made to pick up the target in the light and carry on to a depth-charge attack. Considerable difficulty was experienced in picking up the target with the light. This was somewhat alleviated by carefully given homing instructions and range information from the radar operator. The British developed a radar system which automatically directed the light on the target.

5.3.4 Identification of Friend or Foe

The reader may have gathered from the previous paragraphs that it was not customary to drop bombs on a target picked up by ASV equipment unless a visual contact was also achieved. Such, unfortunately, was true. During the early stages of World War II, some Allied vessels were not outfitted with equipment for identifying friend from foe [IFF] and even after all vessels were so equipped, there was a continued lack of faith in the infallibility of IFF and pilots were required to make visual as well as radar contact. (This was not true in those areas considered to contain only enemy shipping.) The lack of IFF or lack of faith in IFF imposed serious limitations on ASV tactics. For example, a plane often had to deviate far from its patrol course just to look at a friendly vessel. Or again, as mentioned above, aircraft intended for night operations often were loaded down with heavy searchlights, thus decreasing either gas or bomb load.

In view of the existence of excellent low-altitude radar computers (see Sections 8.4.1 and 8.4.2), the handicap imposed on ASV operations by the IFF situation becomes obvious. Future ASV planning should consider the importance of developing IFF on a par with developing good radar.

5.4 SUMMARY

As stated before, the primary function of ASV radar is to detect: (1) surface vessels and (2) subsurface vessels operating with only a small part such as the Schnorkel tube exposed. The secondary function is navigation. A system known as the *airborne early warning* [AEW] has been designed and flown which is capable of detecting coast line at 200 miles and small surface vessels at 120 miles. Thus the secondary function and the first half of the primary function of ASV radar has been accomplished, in so far as the horizon limitation permits, for all but the greatest altitudes. It does not seem unreasonable to assume that an extension of present radar techniques would permit the detection of surface vessels on the horizon by a plane flying even at 50,000 ft.

On the other hand, the best ranges that have been obtained on a Schnorkel using the most modern techniques is less than 20 miles. This is the big problem facing the designer of an ASV system today, and it is an urgent problem, for recent developments seem to emphasize the importance of the undersea vessel as a weapon of war. The obvious direction of attack would be to design higher-powered radar systems with larger antennas and more sensitive receivers incorporating improved anti-sea-return circuits. Common sense would indicate, however, that there is a limit as to how far it is possible to go in such a direction, for the equipment becomes too large and heavy to be airborne. Present techniques indicate that this limit would be reached before a satisfactory maximum range on the Schnorkel was obtained.

Thus, in closing, it is suggested that although radar has succeeded admirably in fulfilling most of the requirements of an ASV system, radar may not be the answer to the Schnorkel.

PART II

RADAR BOMBING

Chapter 6

THE BOMBING PROBLEM

6.1 RADAR BOMBING

The use of radar for over-land bombing was a logical development of its *air to surface vessel* [ASV] application. The following chapters will describe some aspects of the bombing phase of military airborne radar which greatly increased the effectiveness of airplane warfare during World War II. In particular, an attempt has been made to describe the technical development of radar bombing computers as well as the requirements that the radar system had to fulfill. Wherever possible, the advantages and disadvantages of various bombing schemes are discussed although no attempt is made to evaluate critically the several bombing methods.

In this chapter, the geometry of bombing and its general nature are described. The treatment of the bombing problem is specialized in that the airplane is assumed to fly a straight and level course and to maintain the same altitude on the bombing approach. A more generalized case is discussed in Chapter 9 although there also the airplane is assumed to be flying at constant altitude. A brief description of the Norden optical bombsight is given in the present chapter since it is intimately connected with the development of radar bombing computers.

Chapter 7 lists several airborne radar mapping systems that are used for bombing and gives the requirements that bombing places on them. Chapters 8 and 9 describe several types of radar bombing computers that are used with airborne radar systems.

Chapters 10 and 11 describe bombing methods that make use of radar installations on the ground as well as in the airplane. In Chapter 10, beacon bombing schemes such as Oboe and Gee-H are considered and bombing by use of radar gunlaying equipment is discussed in Chapter 11.

Toss bombing is discussed in Chapter 12. Although this is a method of bombing, it is more directly related to fire control (Part IV) than to the other bombing schemes considered here. Since the application of radar to toss bombing has been only partially exploited, further development of this phase of radar bombing is to be expected.

Finally, in Chapter 13, the assessment and training phases of the radar program are considered. As a result of the newness of the radar method, no provision for an adequate radar training program existed at the start of World War II. Although the training program for radar operators and mechanics was well advanced by the end of hostilities, training was a weak link in the radar effort. Chapter 13 recounts some of the flaws and omissions that developed in the hastily devised radar training program.

6.2 GENERAL CONSIDERATIONS

The general problem of bombing from aircraft divides itself rather naturally into four distinct parts. They are: navigation to the target area, identification of the target, computation of a release point, and steering to that release point. In past bombing computers, the greatest emphasis has been placed on computation and steering to the release point and until recently the computer has not assisted in identifying or navigating to the target. This has often caused gross bombing errors in combat because of the resultant faulty navigation and misidentification. It should be remembered that navigation and identification are part of the bombing problem, and indeed a very important part.

6.2.1 Navigation to the Target Area

Fundamentally, all air navigation is based on *dead reckoning*. If the present position of the aircraft is known, then the future position can be determined provided the *ground velocity vector* (consisting of the ground speed and direction on the ground in which the aircraft is moving) is known. Usually the ground velocity vector is obtained from a combination of the *aircraft vector* (consisting of aircraft heading and airspeed) with the *wind vector* (consisting of wind direction and speed). Thus the future position of an aircraft can be forecast if a *point of departure* (a fix), the aircraft vector and the wind vector are known.

The problem of finding the aircraft vector appears comparatively simple, since every plane carries a compass and airspeed meter; but when it is desired to perform dead reckoning with an accuracy sufficiently high for good bombing, this problem becomes rather difficult, and special devices must be employed. These devices will be discussed in a later section.

The wind vector may be found by measuring the drift of points on the ground relative to the aircraft on two different headings. The visual drift meter is the most common instrument for determining the wind vector in this manner. Another method of finding the wind vector is to determine two points of departure, or fixes; if the time lapse between these fixes and the aircraft vector while flying between them are known, the wind vector may be determined. In the following paragraphs, various means of determining fixes, and thus the wind vector, are discussed.

PILOTAGE

Pilotage, though not generally regarded as a form of dead reckoning, might be considered as the most simplified form of dead reckoning, where the wind is more or less guessed at and the points of departure are determined merely by looking at the features of the terrain (either by radar or visually). The recording and combining of the aircraft and wind vectors with the point of departure are performed mentally.

Although pilotage might seem the easiest method of navigation, it is such only under ideal conditions. Unless the navigator is thoroughly familiar with the terrain over which he is flying, any distraction from the job of pilotage, such as visual obscuration of the ground, violent maneuvering when using an unstabilized radar system, or the necessity of handling guns, may cause him to lose his place and valuable fuel may be expended while he finds it again. Some terrain (such as the Midlands of England) appears uniform for long stretches to all but the most experienced navigator, thus necessitating some other method of navigation than pilotage.

On the whole, since pilotage is to such a large extent an art, and depends entirely on the ability to see the ground, and to identify terrain features, it is not to be recommended as a means of combat navigation. A continuous record of the wind vector and of the aircraft position should always be kept, so that, despite injury to the navigator, damage to the radar set, or obscuration of the ground, the pilot will know where he was at the time the emergency arose and can then choose a course to his home base. Such continuous navigation plots were found to be very necessary and hence were greatly emphasized by the RAF during World War II.

CELESTIAL NAVIGATION

Celestial navigation is a means of obtaining points of departure from sightings on celestial bodies so that dead reckoning may be carried out. Although this is a reliable and fairly accurate method of navigating an airplane, it does have several disadvantages for combat navigation.

In the first place, it assumes the absence of an overcast. This is often a poor assumption, particularly under combat conditions when weather forecasting becomes difficult and when missions must be undertaken despite forecasts of bad weather.

Secondly, in order to obtain any reasonable accuracy in the sightings, and thus in the point of departure, the plane must provide a stable platform for the navigator. This is not always possible under combat conditions or in rough air.

Finally, even if the above conditions are satisfied, the accuracy of the point of departure found is not high since it is about plus or minus 5 miles.

The foregoing disadvantages, together with the need for freedom from mental stress during the navigator's somewhat complicated computations, make celestial navigation undesirable for combat missions. A permissible exception would be a long over-water flight where other means of obtaining points of departure are nonexistent.

INSTRUMENT NAVIGATION

The most common type of instrumental aid to navigation is the radio compass, by means of which one or more lines of position may be found if ground radio stations of known positions can be received. The radio compass loses its general usefulness under combat conditions, however, for the aircraft often are out of range of friendly transmitting stations and the radio system may be jammed easily. A variation on the radio compass type of aid is the ground-based direction finding station. Nets of such stations with central plotting rooms have been used very successfully to give rapid fixes to aircraft within range of the stations. The main drawbacks to such chains are the rather limited range and the overloading of their facilities if many planes want fixes simultaneously.

One of the more generally satisfactory navigational instruments developed during the war is the so-called *hyperbolic system*, which includes GEE and Loran. These systems consist of two pairs of synchronized stations transmitting pulses at fixed intervals of time. The GEE or Loran receiver permits the navigator to measure the difference in time between the arrival of the pulses from the various stations and thus, with a special map on which lines of equal time difference are plotted, he can immediately get a good fix. These systems suffer somewhat from jamming, but require little effort and thought of the navigator (see Chapter 10).

Another highly satisfactory method of obtaining points of departure, and thereby the wind vector, is by the use of radar mapping systems. When land is within radar range, these systems offer pilotage despite darkness or undercast, complete independence of ground-based stations, and relative freedom from jamming. Radar beacons may be used with such mapping systems, permitting the navigator to measure the range and direction of beacons of known position on the ground. These beacons are relatively jam-proof and may be received almost out to the horizon.

Up to the horizon range or slightly less, airplanes equipped with a simple radio communication system may be accurately positioned by means of ground-based radar stations. The rather low traffic capacity of this method of navigation as well as the identification problem and ease of detection by the enemy limits its usefulness to special missions or to the handling of airplanes in distress.

CHOICE OF NAVIGATIONAL INSTRUMENTS

As may be seen from the foregoing, there are many means of finding points of departure and the wind vector. Because of the several types of missions for which airplanes are designed, it is impossible to make any generalization as to what equipment should be included in all aircraft. Several factors must be kept in mind by the designer. He must insist, above all, on reliability, and then upon simplifying the task of the navigator. He must adjudge weight and size, realizing that additional weight may be worth while if it means navigational equipment sufficiently accurate to serve also as a bombsight. In the following sections the adaption of various navigational types of equipment to bombing will be considered.

A more complete treatment of air navigation may be found in the R. L. Technical Series and elsewhere.[52, 111]

6.2.2 Identification of the Target

The location of a target can be determined in two ways, first, by seeing and recognizing it and second, by making a survey to determine its position in relation to known positions on the earth's surface. In general, the visual bombsights depend entirely upon the first method for identification, while the radar techniques involve both.

How well the target can be seen depends upon the resolving power of the sighting unit, the contrast between the target and its background, and the presence of obstructions. The ability to see is further affected by the distance from the target and its size. Once it has been seen, recognition will depend upon its characteristic size, shape, color (if observed visually), and surroundings. The ability to recognize targets will also depend upon the permitted observation time and the relative velocity of aircraft and target.

The second method is not identification but rather eliminates the need for identification. It consists of making a survey of present aircraft position and comparing this with the known position of the target, as given by a map or other previous survey data. If the aircraft is maneuvered to be over the surveyed position of the target, it can be said the target has been located by a method of surveying, whether it can be "seen" or not. The most familiar bombing methods using these principles are the radar beacon systems (see Chapter 10).

The methods which are actually used for location of the target include those using only sight, those using a combination of sight and survey, and those using only survey. The visual bombsights, because of their inherently high resolving power, permit a bombardier to see the distinguishing characteristics of a target; therefore he is able to use vision for identification with much greater likelihood of success than the radar bombsights. On the other hand, darkness, haze, and cloud cover obstruct visual sights so that it is often not possible to see the target, much less identify it. For this reason and others, it is desirable to use radar sights. However, the angular resolving power of a radar system is poor with present equipment (see Section 7.1.1). This may result in radar pictures of the target which are not recognizable, or, at best, are only recognizable by an operator who has had considerable training in radar scope interpretation. One technique developed to ease the task of the operator is to use well-defined radar reference points as aiming points, and then, by a method of surveying, to identify the target and bomb it whether it is seen or not. This is called offset bombing and employs in this case both radar sight and surveying. Other techniques employ radar beacons for surveying and synchronizing a visual bombsight with the target. After the initial location of the target by use of the beacons, these methods depend upon the inherent high resolving power of the visual bombsight to make an accurate bomb run.

The main difference between visual recognition and survey types of identification or location is that the former depends upon the judgment of an operator, whereas the latter is done by a (mechanical or electrical) computer. Since the operator is human and flying under adverse conditions, it is entirely reasonable to expect greater errors in the former than in the latter case. This is illustrated by the bombing accuracy figures of both visual and radar bombardiers in and out of combat. In both cases, bombardiers used discrete, well-identified points as targets in practice, and complex targets in combat; the result was much poorer bombing when it really counted. However, bombardiers using surveying computers which were automatic, achieved much more nearly the same results in combat as in practice.

In conclusion, it should be stated that the problem of target identification is one which until recently received far too little attention. The excellent results given by beacon bombing systems tend to show that if the problem of identification is removed from the control of the operator and put into the bombing computer, the overall accuracy will be much greater. Since most beacon bombing systems are effective only out to the horizon of the ground-based beacon, other bombsights are needed which are capable of giving good results out to the limit of the range of the aircraft. It is apparent, therefore, that the problem of identification should, in some manner, be solved for the computers which are used for bombing by sight (visual or radar), since these computers can be used at any range. A step in this direction has been taken by the *ground position indicator* [GPI] computer discussed in Chapter 9.

6.2.3 The Computation of Release Points

The computation of release points can be made in many ways. However, regardless of how it is done, the same fundamental data are necessary. A release point is, by definition, a point in space at which a missile can be released so that it will hit the desired target. Actually, for each target there are an infinite number of possible release points, each dependent upon the conditions under which the missile is released. In this discussion, the release point will be considered for missiles which are released from an aircraft with the object of hitting an air, land, or sea target; in each case, the missile is carried to the release point by the aircraft and is released at the speed and with the heading of the aircraft.

The following list of definitions covers special terminology used in further treatment of the bombing problem:

True airspeed ($\mathbf{V}_a$) is the velocity of an aircraft relative to the air mass in which it is flying. True airspeed is measured in the direction of the aircraft's heading.

Wind ($\mathbf{W}$) is the velocity of the air mass relative to the earth. Convention assumes the wind to be acting in a direction opposite to that indicated by its name, i.e., a north wind indicates a movement of the air mass from north to south.

Ground speed ($\mathbf{V}_g$) is the velocity of an aircraft relative to the earth.

Ground track is the direction of the ground speed vector, or the path of the aircraft as it passes over the earth.

Drift angle (δ) is the angle between aircraft heading and the ground track.

Time of fall (T_f) is the time from release to impact of the bomb. It is a function of the altitude and the resistance of the air to the bomb's fall.

Trail ($\mathbf{T}_R$) is a measure of difference between the impact point where a bomb actually hits, and where it would have hit if it had fallen without losing horizontal speed due to air resistance. Trail is measured in the direction of the aircraft's heading and is a function of the type of bomb, the initial velocity of the bomb, the resistance due to air, and the time of fall.

Cross trail ($\mathbf{T}_x$) is the perpendicular distance measured from impact point to the ground track. It is equal to the sine of the drift angle times the trail.

In general, to compute a release point, it is necessary that the following information be available in one form or another:

1. Velocity of the missile relative to the target at release time.
2. Velocity of the missile relative to the air mass at release.
3. Characteristics of the missile after release.
4. Altitude of missile at release.

It is then possible to state that a missile released at a particular distance and direction from the target would hit the target, providing each of the items mentioned is known and the target is assumed to be moving with a constant velocity. However, since it is difficult to build computers to solve bombing problems in a completely general fashion, the behavior of the airplane on the bombing run is usually restricted in some particular manner. Further complications exist in the very measurement of input data, since mechanisms do not exist which present all the data in the exact form desired for computation. Because of these complications of computing release points, most of the present-day bombsights have required that the airplane be flying straight and level at release point. Under these conditions the geometry used for the determination of release point is that shown in the vector diagram of Figure 1.

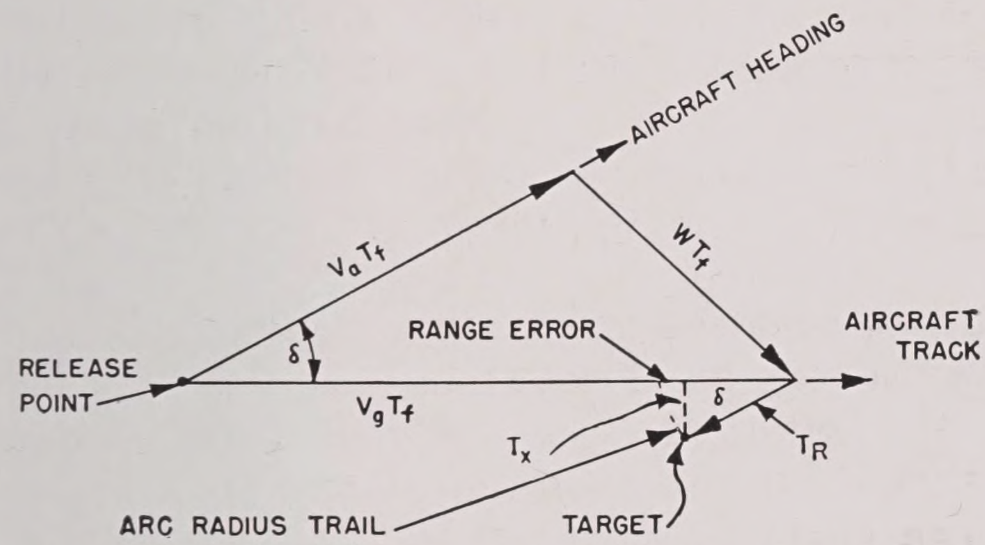


FIGURE 1. Geometry of bombing.

This geometry makes possible a rigorous solution for the bombing problem regardless of altitude. The altitude factor, of course, enters into the magnitude of time of fall and trail. The various existing computers use some form of this solution, although, in some cases, approximations are made. The most common approximation is to assume trail to act in the direction of the ground track, and then make a correction for the resulting deflection error, which is trail times the sine of the drift angle (cross trail). This gives a solution which is correct except for a higher order range error sometimes known as the range component of cross trail.

It is possible to compute a release point by making assumptions such as to the airspeed, wind, and altitude that should exist during the bombing raid. The airplane is then required to satisfy those conditions during the actual bombing run. Under such circumstances a large amount of maneuvering and possibly repeated runs will be required to satisfy the conditions for which the release point was computed. The more satisfactory technique is to employ computers that solve for the release point corresponding to the values of airspeed and wind which exist on the actual bombing approach.

6.2.4 Steering to the Release Point

Once the point at which bombs should be released has been computed, the problem of maneuvering the bombing aircraft to that point still remains. To be able to do this, it is necessary that the present position and ground speed vectors be known. The factors which are most used in determining present position are altitude, bearing of target relative to aircraft heading, angle of inclination from horizontal to target, and range to the target. Generally speaking, the visual bombsights make use of altitude and angle measurements, while the radar sights rely on slant range and bearing angle.

The geometry used to steer the aircraft to the release point, regardless of the mechanism by which it is done, is shown in Figure 2. From this drawing it can be seen that it is necessary for the computer to be able, in some manner, to make the ground track of the aircraft (OC) coincide with that of the release geometry (OD). One method could be to indicate the difference between present and desired heading (θ) to the pilot so he can steer the correct heading. Another method could be to give the pilot an indication as to when the ground track of the aircraft passes through a point (E) displaced from the target by the cross trail ($\mathbf{T}_x$). Assuming now that the steer-

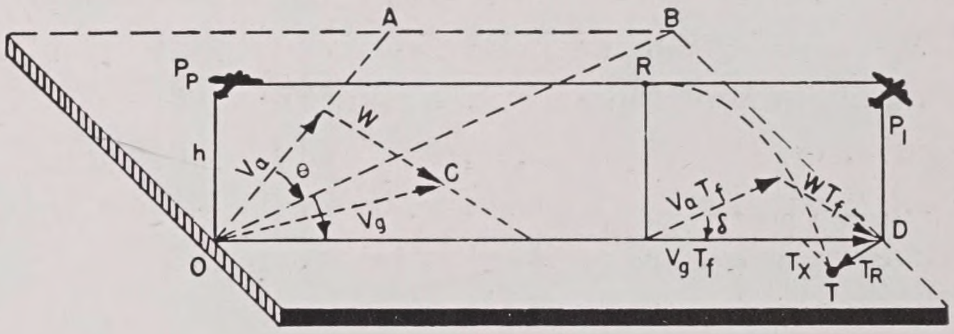


FIGURE 2. Geometry of steering.

ing is correct, it is necessary to indicate when the aircraft reaches the release point. This can be done in several ways, one of which is to compare the present and the release ground range (or slant range) to the target; when the present range equals the desired value, the release occurs. Another would be to compare the present and desired sighting angle to the target. Sighting angle is the angle between a line from aircraft to target and the vertical. Once again when the instantaneous value becomes equal to the desired value, the bombs will be dropped.

Since there are so very many different ways in which the bombing geometry can be solved, it is impossible to consider each one here. However, in the next two chapters, the geometry will be discussed for several radar bombing computers.

6.3 SOLUTIONS OF THE BOMBING PROBLEM

6.3.1 The Visual Method The Norden Bombsight

In the previous sections the general level bombing problem was outlined. Evidently, many solutions are possible by either visual or radar means. Before considering in detail the several radar solutions that were developed during World War II, it seems advisable to give a short description of the Norden stabilized synchronous bombsight, since it was the visual bombsight most universally used by the U.S. Army and Navy and has influenced to some extent the development of radar bombsights.

The Norden bombsight may be divided into four parts which are the rate end, the telescope and mirror, the vertical gyro, and the horizontal gyro or stabilizer.

The Rate End

The rate end solves the range triangle for the tangent of the release angle which is equal to $| \mathbf{V}_g T_f - \mathbf{T}_R |(1/h)$, where $\mathbf{V}_g$ is the ground speed, T_f is the time of fall of the bomb, $\mathbf{T}_R$ is the trail, and h is the altitude. The solution is performed by a constant-speed motor driving a disk upon which bears a roller (see Figure 3). The roller, in turn, drives the mirror, into which the telescope looks, so as to keep the range cross hair in the telescope constantly on the target.

The rate of the constant-speed motor is controlled by the disk speed knob on the outside of the rate end,

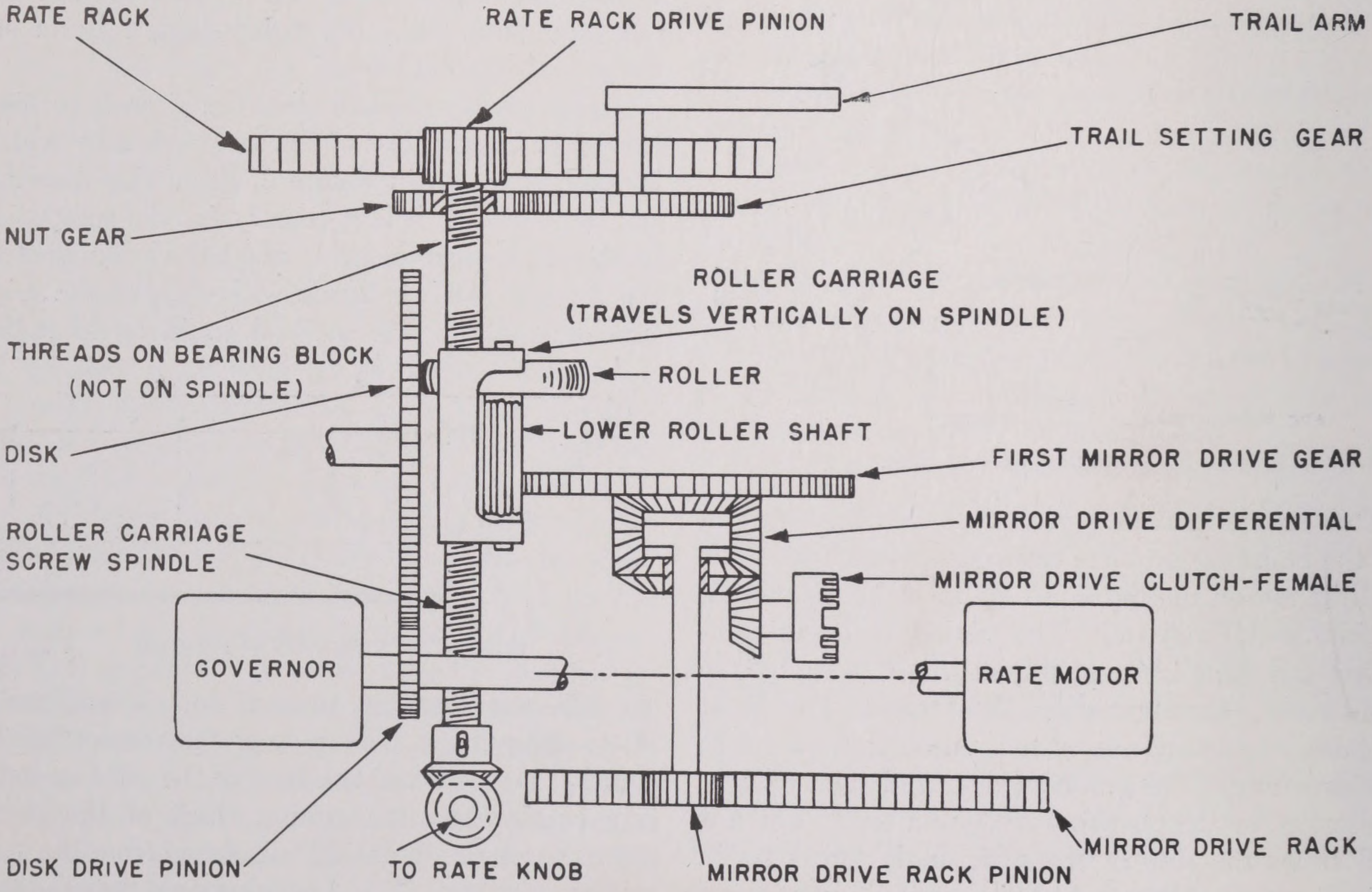

RATE RACK
RATE RACK DRIVE PINION
TRAIL ARM
TRAIL SETTING GEAR
NUT GEAR
ROLLER CARRIAGE (TRAVELS VERTICALLY ON SPINDLE)
THREADS ON BEARING BLOCK (NOT ON SPINDLE)
ROLLER
LOWER ROLLER SHAFT
DISK
FIRST MIRROR DRIVE GEAR
MIRROR DRIVE DIFFERENTIAL
ROLLER CARRIAGE SCREW SPINDLE
MIRROR DRIVE CLUTCH-FEMALE
GOVERNOR
RATE MOTOR
DISK DRIVE PINION
TO RATE KNOB
MIRROR DRIVE RACK PINION
MIRROR DRIVE RACK

Figure 3. Norden bombsight mirror drive and rate and trail setting. Schematic diagram.

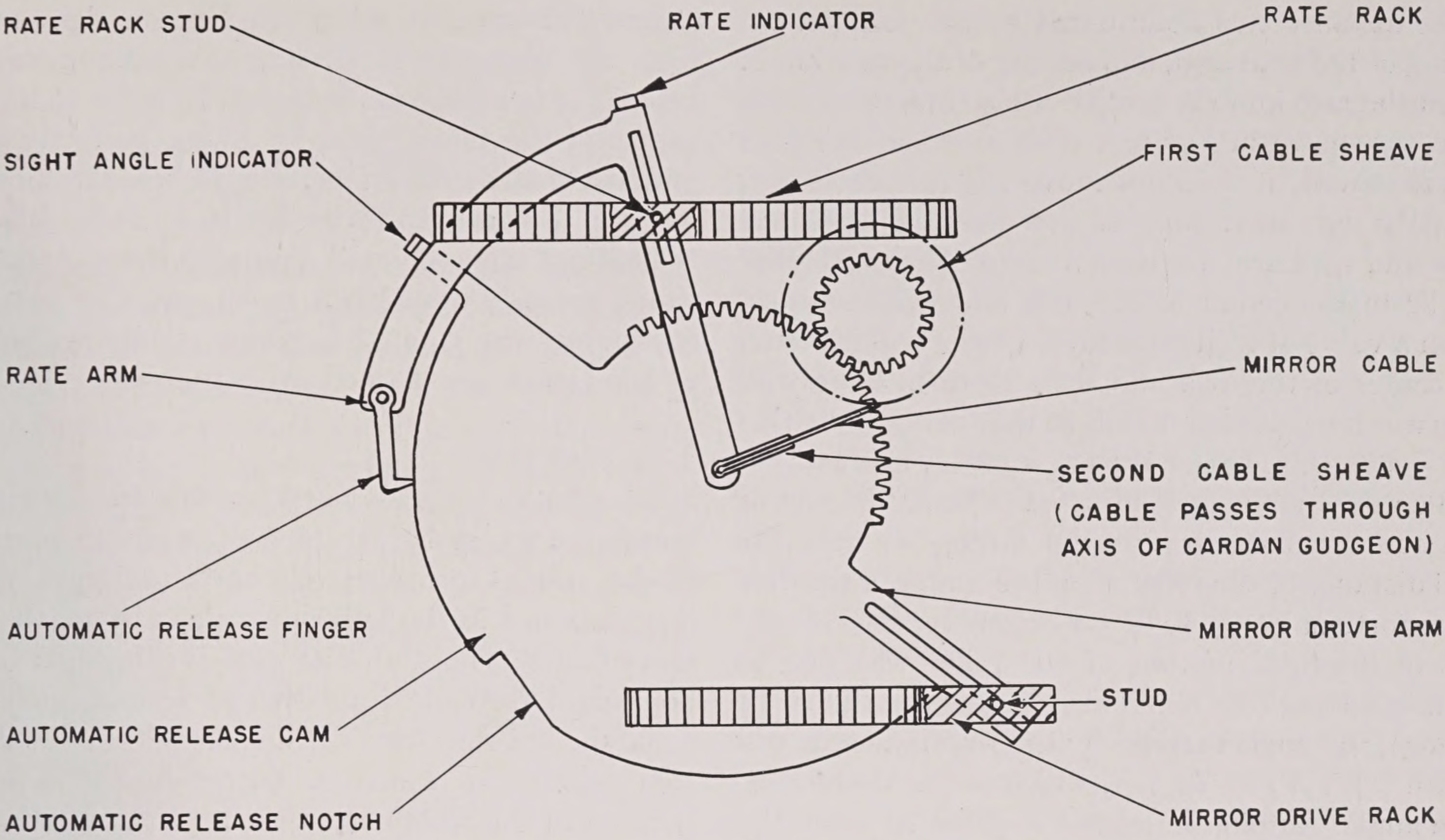

RATE RACK STUD
RATE INDICATOR
RATE RACK
SIGHT ANGLE INDICATOR
FIRST CABLE SHEAVE
RATE ARM
MIRROR CABLE
SECOND CABLE SHEAVE (CABLE PASSES THROUGH AXIS OF CARDAN GUDGEON)
AUTOMATIC RELEASE FINGER
MIRROR DRIVE ARM
STUD
AUTOMATIC RELEASE CAM
AUTOMATIC RELEASE NOTCH
MIRROR DRIVE RACK

FIGURE 4. Norden bombsight mirror drive. Schematic diagram.

and is equal to K/T_f, where K is a constant of design. The distance of the roller from the center of the disk is controlled by the trail-setting arm and by the rate knob.

The roller speed is constant for a given disk speed setting and a given distance between the roller and the center of the disk. The roller is geared to the mirror drive rack which carries a stud in one end which engages a slot in, and thereby drives, the mirror drive arm. (See Figure 4.) The mirror drive arm, therefore, swings at a varying rotational velocity, so that, for the correct roller speed, the line of sight of the mirror remains pointed at the same area of the ground throughout the bombing run.

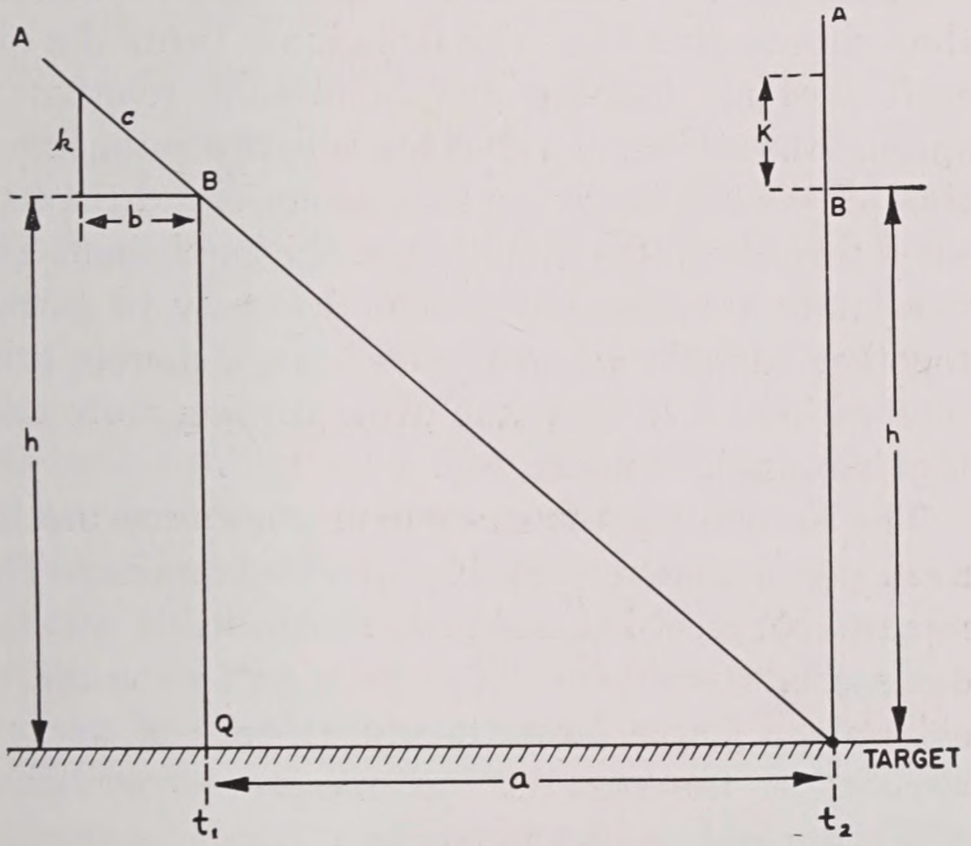

A
c
k
B
b
h
Q
a
t₁
A
K
B
h
TARGET
t₂

FIGURE 5. Geometric function of mirror drive rack.

The rack speed, or roller speed, which is necessary to synchronize the mirror on a given spot on the ground is $|\mathbf{V}_g k|/h$, as may be seen from the following. Suppose that at time t_1, the airplane is over point Q which is at a distance a from the target, and at time t_2 the airplane is directly over the target. (See Figure 5.) If the line of sight of the mirror is along the line AB and its direction is determined by the triangle with the sides k, b, and c, where k is of fixed length, and b is the rack length necessary to point the mirror at the target, then at time t_2, it will be seen that the rack length must be zero. Also, since there are two similar triangles, $b/a = k/h$, or $b = ak/h$. Divide both sides by $(t_2 - t_1)$. Since $a/(t_2 - t_1)$ equals $|\mathbf{V}_g|$, the ground speed, while $b/(t_2 - t_1)$ is the rack speed R_s, $R_s = V_g k/h$.

As previously stated, the rack speed is determined by the disk speed D_s and the distance d of the roller from the center of the disk. Thus R_s is proportional to $D_s d = Kd/T_f$. Combining the two expressions we have obtained for the rack speed, it will be seen that d is proportional to $|\mathbf{V}_g T_f|/h$, for synchronization on the target.

The distance d is determined by two factors: the setting of the trail arm, and setting of the rate knob. When the rate knob is turned, it also moves the rate indicator shown in Figure 4 whereas when the trail arm is moved, it does not move the rate indicator, but only the roller. Suppose now that the rate indicator and trail arm are both at zero. Then the roller will be in the center of the disk and will not turn. When a value of trail is set in, the roller will move off the center of the disk and start to turn. (The trail indicator is graduated in mils so that actually a value of $d = |\mathbf{T}_R|/h$, rather than $d = |\mathbf{T}_R|$, is set in.)

The rate knob is now adjusted to bring the mirror into synchronization with the target, so that the total distance of the roller from the center of the disk is proportional to $|\mathbf{V}_g T_f|/h$. However, since only part of the total motion of the roller was due to the rate setting (the remainder coming from the trail setting), the angle marked by the rate indicator will be $\tan^{-1} |\mathbf{V}_g T_f - \mathbf{T}_R|/h$, which is the desired release angle. Automatic release is obtained when the sighting-angle indicator coincides with the rate indicator as shown in Figure 4.

The Mirror and Telescope

The mirror and telescope assembly is of importance not simply for the purpose of seeing the target, but also because it provides a method of setting in the cross trail correction. By means of a complicated system of levers and cams, the trail angle is multiplied by the sine of the drift angle and the whole telescope and mirror assembly is tilted proportionately, so that the ground track of the plane appears to pass through the target, although actually it passes to one side by an amount equal to the cross trail.

The Vertical Gyro

In order to measure the sighting angle to the target accurately, a vertical reference line is necessary. Such a vertical is provided by a gyroscope that is incorporated in the sight. This gyro is connected to the mirror and telescope assembly in such a manner that once the gyro has been brought into the vertical, it will maintain the main axis of the assembly vertical, although, as mentioned above, the assembly may be tipped from its main axis by an amount proportional to cross trail.

The gyro is provided with two precessing knobs and two bubble levels so that its axis may be brought into the vertical. Perhaps the greatest source of instrumental error in using the Norden sight arises from the necessity of leveling this sight gyro just before the bombing run is begun. In order to level it properly, the plane must be flying perfectly even and free of all accelerations, and the bombardier must be free to concentrate on his task. It is difficult, though not impossible, to obtain all these conditions simultaneously when flying in combat, thus partially explaining why combat bombing results are seldom as good as those obtained while training.

The Stabilizer

In order to set up a reference line from which to measure drift, and thus solve the azimuth problem, the bombsight incorporates a horizontal gyro, which is maintained in the horizontal plane by means of a servo motor. This stabilizer gyro is connected to the bombsight through a mechanical system, including a clutch, and thus fixes the line of sight in one direction relative to space. A potentiometer is incorporated in the stabilizer, with the winding attached to the stabilizer case which is fixed relative to the aircraft, while the potentiometer arm is attached to the gyro through a clutch. Then, by using the electrical information supplied by the potentiometer the aircraft may be returned to its original direction either by the pilot using a *pilot's direction indicator* [PDI], or by the automatic flight control equipment whenever the aircraft turns away from the direction indicated by the gyro.

There are two knobs on the bombsight for solving the azimuth problem. The drift knob turns the aircraft without turning the bombsight relative to space, thus setting in a drift angle between the line of sight of the bombsight and the aircraft, and the turn knob turns both the aircraft and the bombsight. The two knobs are arranged so that they may be turned together (double gripped) and have a double gripping ratio of 5.25 to 1 (the plane turning more than the drift angle is increased).

The Norden sight is an extremely accurate mechanism permitting remarkably precise bombing. This remarkable precision, however, is obtainable only under special circumstances, such as perfect visibility, calm air, a stable aircraft, and absence of nervous tension on the part of the operator — conditions which are seldom met in combat. Thus it is possible that a bombsight not inherently so accurate as the Norden might achieve the same combat record. This last fact should be borne in mind when developing any new bombsight, since the basic problem is not mechanical accuracy, but rather accuracy under combat conditions.

6.3.2 The Role of Radar in Bombing

In general, the accuracy of bombing can be regarded as an inverse function of the work required of the operator, and a direct function of the inherent accuracy of the computer. Since the efforts of a human operator are affected by the confusion, comfort, physical labor, and mental stress under which he operates, many factors should be considered when making assessment of a bombing system. Some of these factors are:

1. Facility with which the computer may be used.
    a. Amount of thinking required of the operator.
    b. Extent to which computer operates automatically.
    c. Extent to which the computer aids in navigation and identification.
    d. Training necessary to use computer satisfactorily.
2. Relationship between time needed for setting data into computer and time available for computations and release. (As aircraft with higher speeds are developed, the latter time will become shorter.)
3. Inherent accuracy of computer.
4. Requirements which computer places on auxiliary equipment (such as compass).
5. Types and visibility of targets to be bombed.

In visual bombing, the operator must make an observation to determine the identity of the target, and then go through a routine procedure of knob turning to drop the bombs. The bombing computer, i.e., the bombsight, establishes the release point and steers the aircraft, but does not aid in navigation. The knob-turning procedure is one which, with sufficient training, can become automatic for the bombardier. The visual sighting procedure requires only training in identification from the air, since the targets are being observed with the eyes that the operator has been using all his life.

The mechanism by which one visual bombsight operates has been given in the previous section. This method is characteristic of all visual sights in that it depends upon the high resolving power of an optical system to give an accurate measurement of dropping angle. The inherent accuracy of such computers as the Norden sight can be high, as has often been shown in practice. This particular computer requires very little maintenance. Moreover the size and weight of the optical computer is not excessive.

As aircraft with higher speeds are used for bombing, the problem of making visual bomb runs will become increasingly difficult. The reason for this is the limit in range at which targets can be seen visually even under the best conditions, so that the use of a high-speed airplane reduces the time available for bombing computations. Offset bombing techniques and radar-visual combinations have been suggested to help this situation. A visual ground position indicator has also been proposed as an answer to the limited range problems of visual bombsights. Such a system would also help in the identification of complex visual targets.

Another shortcoming of visual bombing is the inability to see targets through cloud cover and darkness, or smoke screens. This is the greatest drawback to visual bombing and is the biggest argument for radar.

With the radar bombsight many varied solutions can be made. Usually these depend upon the inherently high range accuracy of radar systems. The facility with which the several computers can be used varies greatly; however, one problem, common to all radar bombsights with the exception of beacon systems, is that of oscilloscope interpretation. Seeing targets on a scope is something new to operators and a certain degree of skill is needed in order to recognize objects. Thus the training required to permit intelligent operation of a radar system is definitely greater than for a visual system. The knob-twisting procedures of radar bombsights, however, can be made just as routine and simple as for their visual counterparts.

The radar systems have an advantage over visual systems when used in high-speed aircraft since they can see farther and thus permit more time for adjustments on the bombing run. Also, of course, radar can be used through clouds, darkness, and smoke.

The inherent accuracy of some radar bombing systems, e.g. Shoran (Chapter 10), can be made as high as that of a visual system. In general, however, radar systems are more complex and require more maintenance.

The following chapters give detailed discussions of some types of radar bombsights. They have been divided into computers for airborne radar mapping systems, beacon bombing systems, ground-controlled bombing systems, and toss-bombing computers. The effective area coverage of the radar mapping bombing systems is far greater than that of the other systems, but mapping systems still place the responsibility for navigation and identification on the operator. Since the bombardier does not have this responsibility when beacon and ground-control systems are used, these have proved more effective than radar mapping systems over the limited areas in which it is possible for them to operate.

Chapter 7

AIRBORNE RADAR SYSTEMS FOR BOMBING

7.1 INTRODUCTION

Although there are many ways in which radar systems can be used for bombing, the greatest part of the radar bombing done in World War II was accomplished by the use of radar mapping systems. As with the optical bombsight, such radar bombing systems are independent of ground installations and restrict the operating range of the bombing airplane only by reducing the gasoline load that may be carried.

The fundamental components of an airborne radar bombing system are: (1) a good navigational radar set, with sufficiently high resolution, (2) a method for accurately measuring distance by radar, and finally (3) a bombing computer that will enable the radar set to drop bombs at the correct release point. It is appropriate that each of these components should be considered in a discussion of airborne radar bombing systems. However, the theory and design of navigational radar systems [51, 52] and of radar ranging circuits [48] have been reported in detail in other publications. In view of this, only the requirements that bombing places on radar systems will be discussed in this chapter. In particular the shortcomings of radar search systems, the principles of radar ranging, and the additional maintenance problems will be briefly considered

Inasmuch as a comprehensive treatment of bombing computers for radar mapping systems is not yet available, an explanation of a number of these computers will be undertaken. In Chapter 8, bombing computers that are designed primarily for establishing the correct bomb-release points will be considered. Finally, a particular type of computer, *ground position indicator* [GPI], that also provides navigational information will be discussed in Chapter 9.

7.2 AIRBORNE RADAR MAPPING SYSTEMS

7.2.1 Fidelity of Radar Mapping

In Chapter 6 the bombing problem was divided into four parts, the first two of which were navigation to the target area and identification of the target. Since these functions of the bombing system are very important and since they are generally performed from the information provided by the radar mapping system, the necessity for well-designed navigational radars is obvious.

Ideally, the *plan position indicator* [PPI] of the radar system should portray as a miniature map the area being scanned by the radar beam. Thus, 10,000 square miles or more of the terrain beneath the aircraft is reproduced on the screen of the radar PPI. The maximum area that can be mapped is determined by the range of the radar system employed and is of considerable interest for navigation over strange country as well as for bombing with high-speed airplanes. A short discussion of the factors affecting range will be given in Section 7.2.2. First, however, the range is assumed to be adequate and the various factors that affect the fidelity with which the features of the terrain are reproduced on the radar map are analyzed.

Some of the distortions that are commonly present in radar maps are:

1. Slant-range, ground-range distortion,
2. PPI spot size distortion,
3. Inadequate azimuth resolution,
4. Inadequate range resolution,
5. Distortion caused by unsatisfactory antenna patterns,
6. Distortions arising from motion of the airplane,
7. Distortions from system errors in range and azimuth.

Each of these factors affecting the fidelity of the radar map will be discussed briefly here, but the reader is referred to the R. L. Technical Series for a more complete analysis.[51, 52]

SLANT-RANGE, GROUND-RANGE DISTORTION

Since airborne radar systems measure directly the distance from the transmitting antenna to reflecting objects on the ground (slant range) the simplest pre-

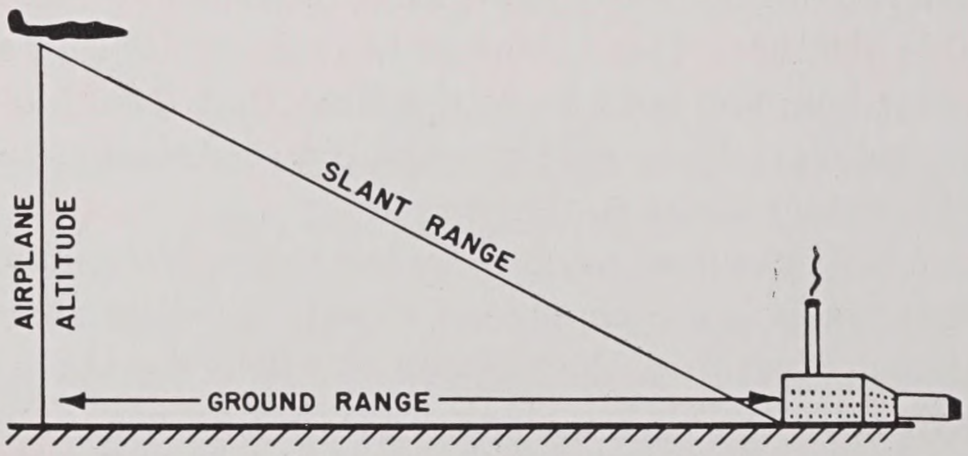


FIGURE 1. Slant range.

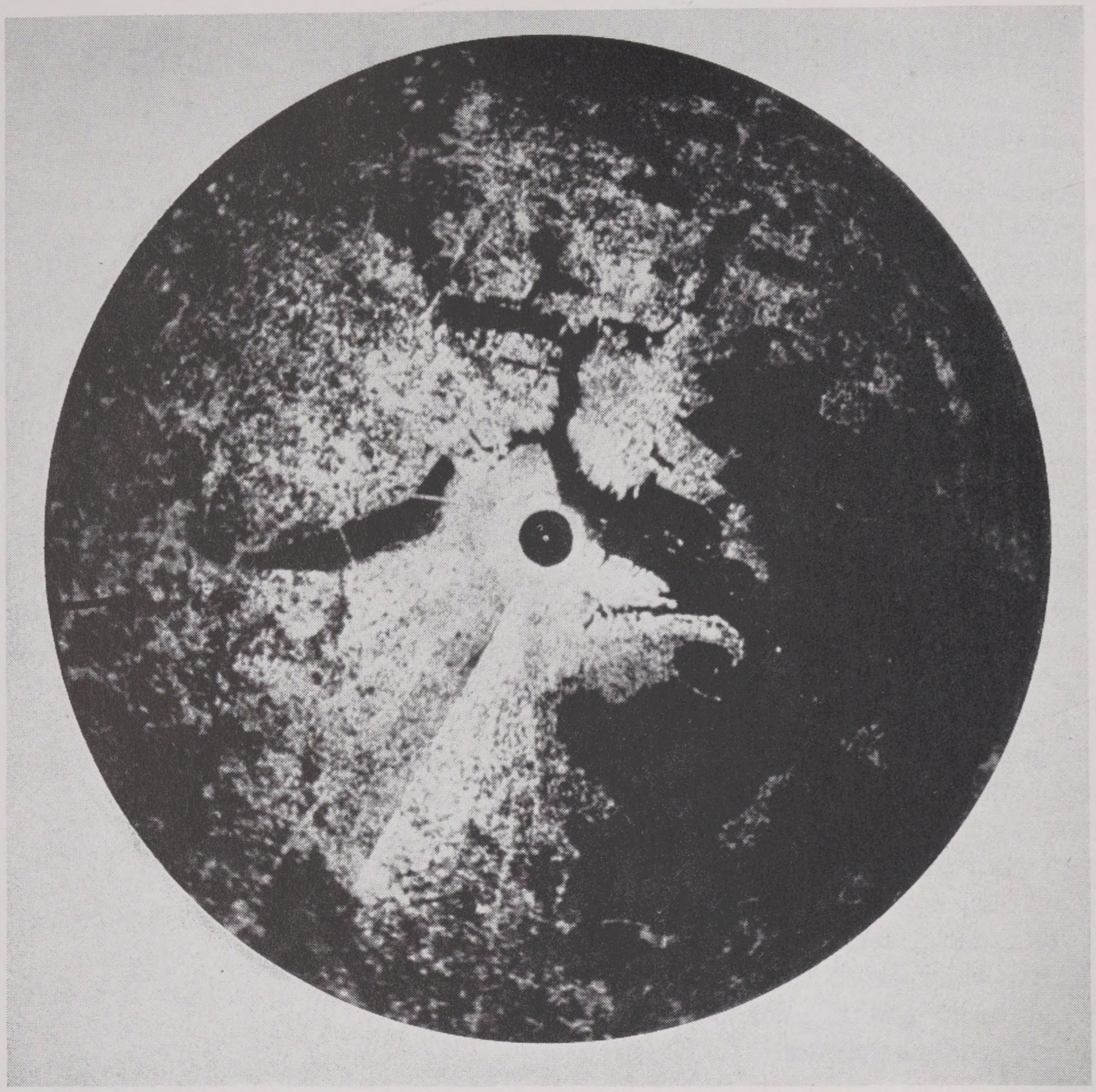


FIGURE 2A. Radar mapping. Radar view of Boston, Massachusetts taken at an altitude of 4,000 ft (radar wavelength 1.3 cm). Range: radius 5 nautical miles ground range. Location of aircraft: 42° 21′ N; 71° 03′ W.

sentation on a PPI depicts the slant range to the target (see Figure 1). At low altitudes, ground range, which is displayed on an ordinary map, is very nearly the same as the slant range and the radar map looks very much like an ordinary map. (See Figures 2A, 2B.)[35] However, as the altitude is increased the slant range differs more drastically from ground range and the radar map is distorted accordingly. It is at once evident that objects almost beneath the aircraft will be foreshortened more than those at a considerable distance. This distortion has a direct bearing on radar bombing because at the time that the bombs are released the ground range rarely exceeds one-half of the slant range to the target.

Another consequence of presenting a slant-range radar map is the absence of signals for slant ranges that are less than the altitude at which the plane is flying. The result is a blank circle in the center of the PPI presentation (see Figure 3). Although this distortion is not troublesome for objects at a considerable distance from the airplane, it greatly affects the radar presentation of a target as the bomb release point is approached. It is common practice to remove this blank circle in the PPI display by synchronizing the start of the radial time base with the return of the first echo, i.e., the echo from the land or water directly beneath the aircraft, the so-called altitude signal. This also introduces distortion but of a different character.[52]

The ideal display would present a ground-range radar map on the PPI by adjustment of the sweep circuits of the PPI tube. For the details of one suitable design, consult the bibliography.[51] Three advantages to bombing from such a display are (1) the radar maps would correspond more closely to the ordinary maps and make identification simpler, (2) all ground objects would move with a constant velocity with respect to the aircraft, and (3) the shape

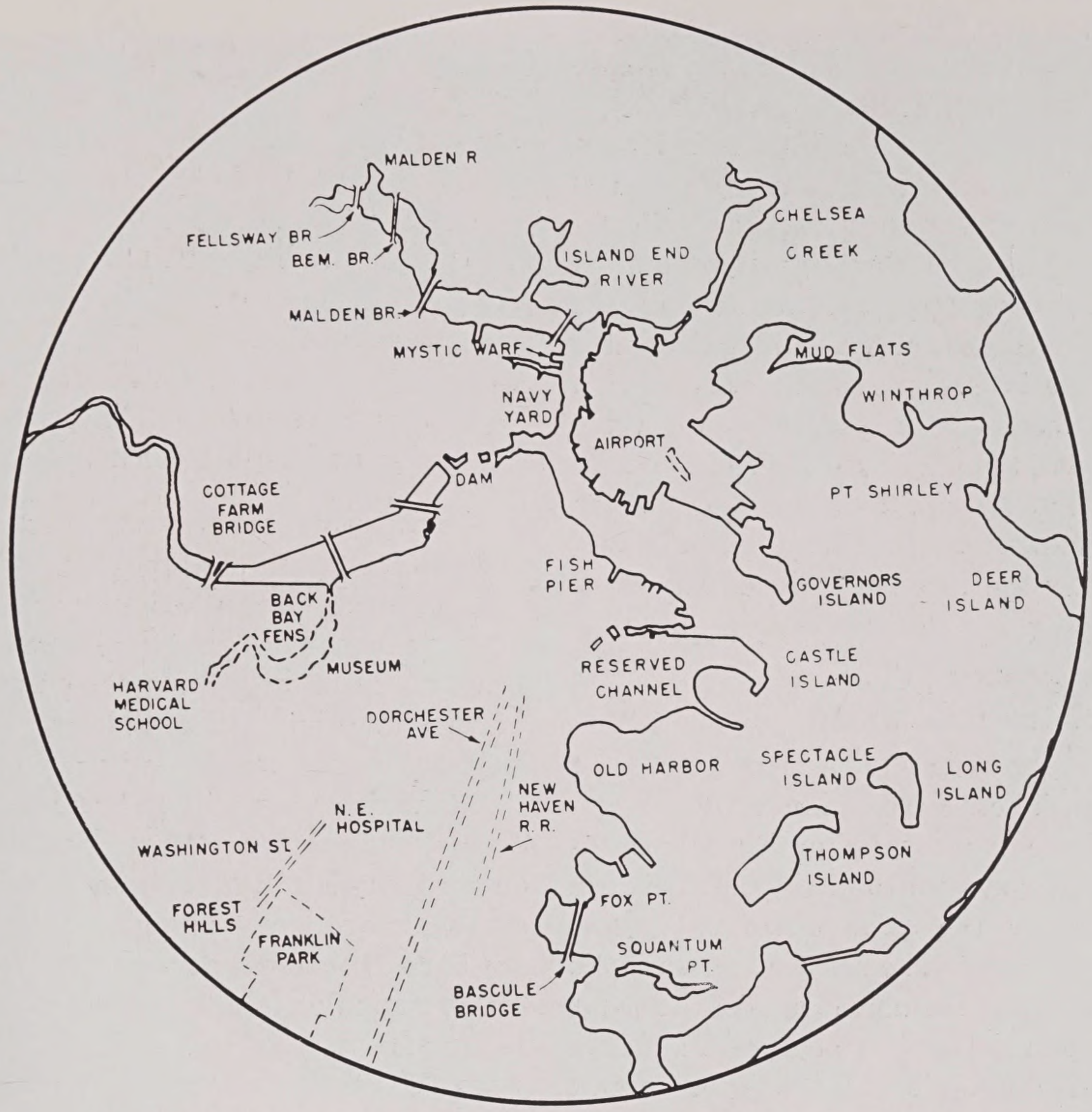

MALDEN R
FELLSWAY BR
B.E.M. BR.
MALDEN BR
MYSTIC WARF
ISLAND END RIVER
CHELSEA CREEK
MUD FLATS
WINTHROP
NAVY YARD
AIRPORT
DAM
COTTAGE FARM BRIDGE
PT SHIRLEY
FISH PIER
GOVERNORS ISLAND
DEER ISLAND
BACK BAY FENS
MUSEUM
HARVARD MEDICAL SCHOOL
RESERVED CHANNEL
CASTLE ISLAND
DORCHESTER AVE
OLD HARBOR
SPECTACLE ISLAND
LONG ISLAND
N.E. HOSPITAL
NEW HAVEN R.R.
WASHINGTON ST.
THOMPSON ISLAND
FOREST HILLS
FRANKLIN PARK
FOX PT.
SQUANTUM PT.
BASCULE BRIDGE

FIGURE 2B. Radar mapping. Ground map of area shown in radar view.

of large ground features on the radar map would not change with range. The second advantage may require a few words of explanation. Where a slant-range presentation is used, objects on the ground toward which the airplane is moving appear to slow down as they are approached, even though the airplane is traveling with constant speed. At large distances from the aircraft, a change in ground range corresponds to a nearly equal change in slant range, whereas, near the airplane, a large change in ground range will correspond to only a small change in slant range, so that for constant ground velocity a reduction in slant-range velocity will be observed. The apparent change in velocity of the target may be disturbing to a radar bombardier who is attempting to track the target on the PPI display.

PPI SPOT-SIZE DISTORTION

Just as the size of his brush determines the fineness of the line that an artist may paint, so also is the detail of a radar map dependent upon the spot size of the PPI. If 2.25 in. on the PPI corresponds to 22.5 nautical miles on the ground then the radar map reduction is approximately 730,000 to 1. Therefore, if the smallest bright spot on the PPI (the spot size) is 0.015 in. in diameter, then the spot size will correspond to 730,000 times 0.015 in. or nearly 1,000 ft in slant range. Under these conditions it would be very difficult to see a river less than 1,000 ft wide on such a radar map. Of course, if the area of the radar map should correspond to less area on the ground, the influence of spot size would be proportionally reduced. The minimum spot size of the PPI also affects the ability of the radar observer to distinguish between objects at about the same range that are slightly different in azimuth.

The spot size distortion may be ameliorated by decreasing the reduction ratio of the radar map through the use of larger PPI oscilloscopes having the same spot size (if such become available, whereas in present designs the spot has a diameter approximately $\frac{1}{250}$ of that of the tube) or by the displacement of the center of the presentation to the side of the PPI so as to increase the map area for the region of interest.

The development of new PPI oscilloscopes with even smaller minimum spot sizes would also be desirable although probably more difficult.

Another aspect of the spot-size problem is its dependence on signal intensity. Thus, a very strong signal will take up more area on the radar map than will a weak signal. Even if such strong signals are limited in amplitude before being applied to the PPI, an effective increase in the size of the picture element is observed, since the intensity of the electron beam hitting the fluorescent screen is at maximum value for a longer period of time. The use of special circuits such as the three-tone presentation (see Section 7.2.2) increases the range of signal amplitude that may be handled by the PPI and reduces this effect on spot size.

Inadequate Azimuth Resolution

Resolution of radar systems is a measure of their ability to distinguish between small reflecting objects that are close to one another. Azimuth resolution is the ability of a radar system to distinguish between objects at essentially the same range but which differ slightly in azimuth. The azimuth resolution is directly dependent upon the narrowness of the radar beam when viewed in the horizontal plane. The beam is too wide to resolve two objects, if it has not stopped illuminating one before it starts to illuminate the other. This means that the radar system sees a continuous signal, such as would be returned from a single object, rather than from several separated objects.

The width of the beam is inversely proportional to the width of the horizontal aperture of the radiating antenna and is directly proportional to the wavelength of the emitted radiation. Thus a very wide antenna, if used with radiation of short wavelength, would have a very narrow beam. Mathematically it can be shown that

$$\Theta = \alpha\left(\frac{\lambda}{d}\right),$$

where Θ = azimuth beamwidth (the angular separation of the two points on either side of antenna beam where the power is one-half of the maximum power emitted in the center of the beam),
α = constant depending on the type of antenna and definition of d,
λ = wavelength of the emitted radiation,
d = horizontal aperture of the antenna.

The horizontal beamwidths of some airborne radar systems are given in Table 1.

It is apparent from this table that good resolution for antennas of moderate size requires the use of wavelengths of approximately 1 cm. Unfortunately, range and propagation problems arise when such wavelengths are used as will be shown below.

Although a very narrow beam would be more desirable, the mapping that is performed with a 1.0-degree beam is satisfactory for identification of parts of cities in overland bombing, particularly when there are harbors, lakes, or rivers nearby. See Figure 2A for an example of mapping obtained by the use of a 1-degree beam.

On the other hand, almost all the radar bombing performed by the USAAF in Europe and Japan employed antennas having a nominal 3-degree beamwidth. (Moreover the apparent beamwidth of the antenna pattern projected on the ground was much greater than this as the target moved under the aircraft.) It may be safely stated that this was not adequate since it resulted in misidentification of many radar targets and was partially responsible for the relatively low number of direct hits. The use of such a broad beam pattern is quite satisfactory for area bombing but is entirely unsatisfactory for bombing a particular factory in a built-up area unless

TABLE 1. Beamwidth of several typical radar systems.

System	Cadillac	AN/APS-15BM or APS-35	AN/APS-15	AN/APQ-13	AN/APQ-7	AN/APS-33	AN/APS-34	K band rapid scan
Wavelength (cm)	10	3.2	3.2	3.2 3.2	3.2	3.2	1.25	1.25
Horizontal aperture of antenna (inches)	96	96	29	29 60	190	29	29	29
Beamwidth (degrees)	3.5	0.85	3	3 1.3	0.4	3.5	1.0	1.0

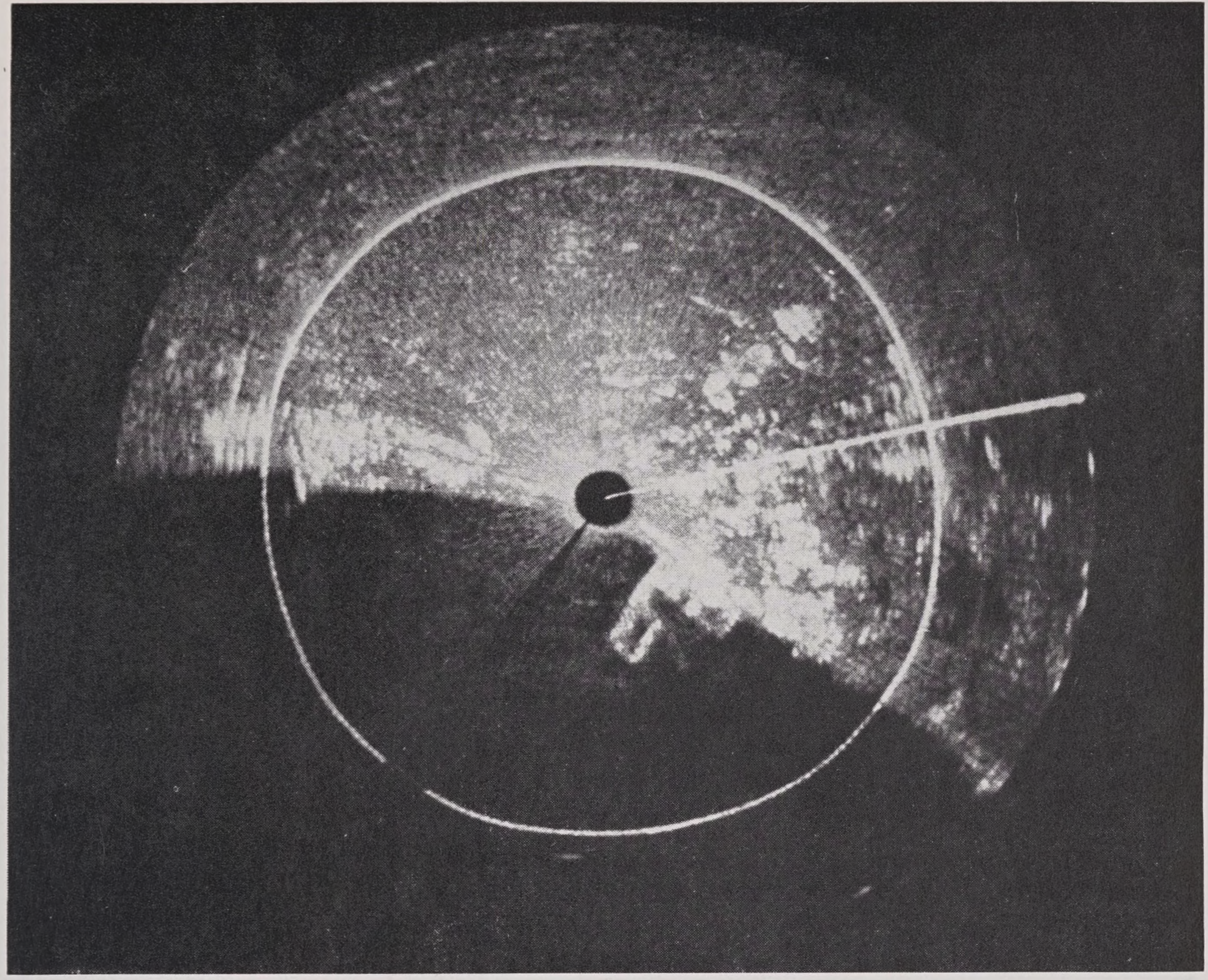


FIGURE 3. Radar display illustrating the dark central "altitude circle."

exceptional care is taken in briefing and in the choice of target. On the other hand, the success of AN/APQ-7 (Eagle) bombing in Japan indicates the precision that may be obtained with the 0.4-degree beam pattern when well-trained crews are used.[83]

INADEQUATE RANGE RESOLUTION

Just as the beamwidth of the antenna determines the azimuth resolution of the radar mapping, the range resolution is set by the duration of the pulse and by the receiver bandwidth, which determines the faithfulness with which the radar receiver detects and amplifies the echo pulse. When the range resolution is just sufficient to permit distinguishing between two closely spaced targets, the onset of the echo from the more remote of the two must not occur until after the end of the signal from the nearer target. Targets more closely spaced than these would appear as one, since a continuous echo signal would be obtained.

Specifically, with a pulse of 1 μsec duration and adequate bandwidth in the receiver, the range resolution or limit to the separation of distinguishable objects in range would be 0.000001 (sec) times 186,000/2 (miles per sec), which is 0.093 statute mile or about 490 ft. More generally, of course, this spacing will equal the pulse duration times one-half the speed of light and hence varies directly with the pulse duration. However, if use is made of pulse durations shorter than those which can be passed faithfully by the receiver, their full potentialities for range resolution will not be realized and the resolvable target spacing will be more closely proportional to the reciprocal of the i-f bandwidth.

Finally, it might be pointed out that the range resolution described above refers to *slant* ranges and the range resolution on the ground becomes poorer at steep sighting angles because of the larger change in ground range which is then necessary to cause a given change in slant range. The pulse duration and bandwidth are, moreover, important in their effect on the range performance of a radar system and so require that a compromise be made in choosing values for

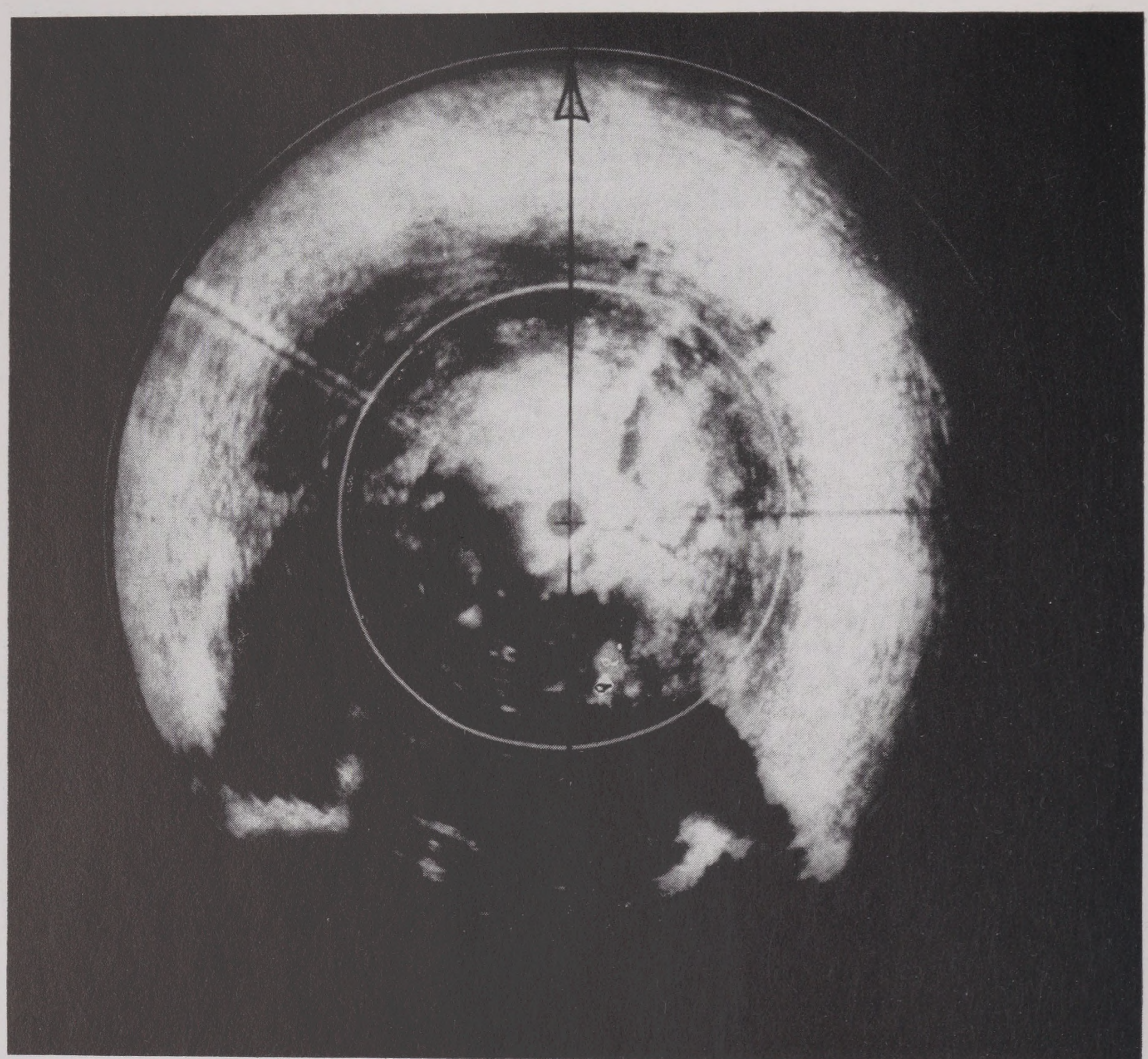


Figure 4A. Radar presentation showing the "ring distortion" caused by a faulty vertical antenna pattern.

these parameters in the design of a complete system. As a result, the minimum pulse duration provided in many production systems has been about 0.25 μsec. In the usual case, it is reasonable to require that the range resolution be at least as good as the azimuth resolution for the ranges in which the observer is particularly interested.

Distortion Caused by Unsatisfactory Antenna Patterns

As already pointed out, the horizontal radiation pattern of the radar antenna is a factor in the fineness of detail that may be presented on the radar map. The vertical pattern, however, determines the intensity of signals at various ranges. In order that the ground be simultaneously illuminated beneath and at a distance from the airplane, the vertical pattern of the antenna is made very broad — usually by reducing the vertical aperture of the antenna. Furthermore, it is desirable to have the echoes of similar ground objects equal in intensity regardless of their range from the aircraft, which makes a special vertical pattern necessary. In most operational radar bombing equipments used during World War II, a cosecant-squared vertical antenna pattern was employed.[50a, 51a] For ground painting rather than the detection of discrete targets a further modification of the antenna pattern will be required.[25]

Departures from the ideal vertical pattern may result in rings of maximum and minimum intensity on the radar map, particularly at short ranges. Such rings in the pattern are objectionable in following a target on the PPI during a bombing run, since it is quite easy to lose the identity of a particular target as it passes through these maxima and minima. This ring type of distortion is shown in Figure 4A.[40] Figure

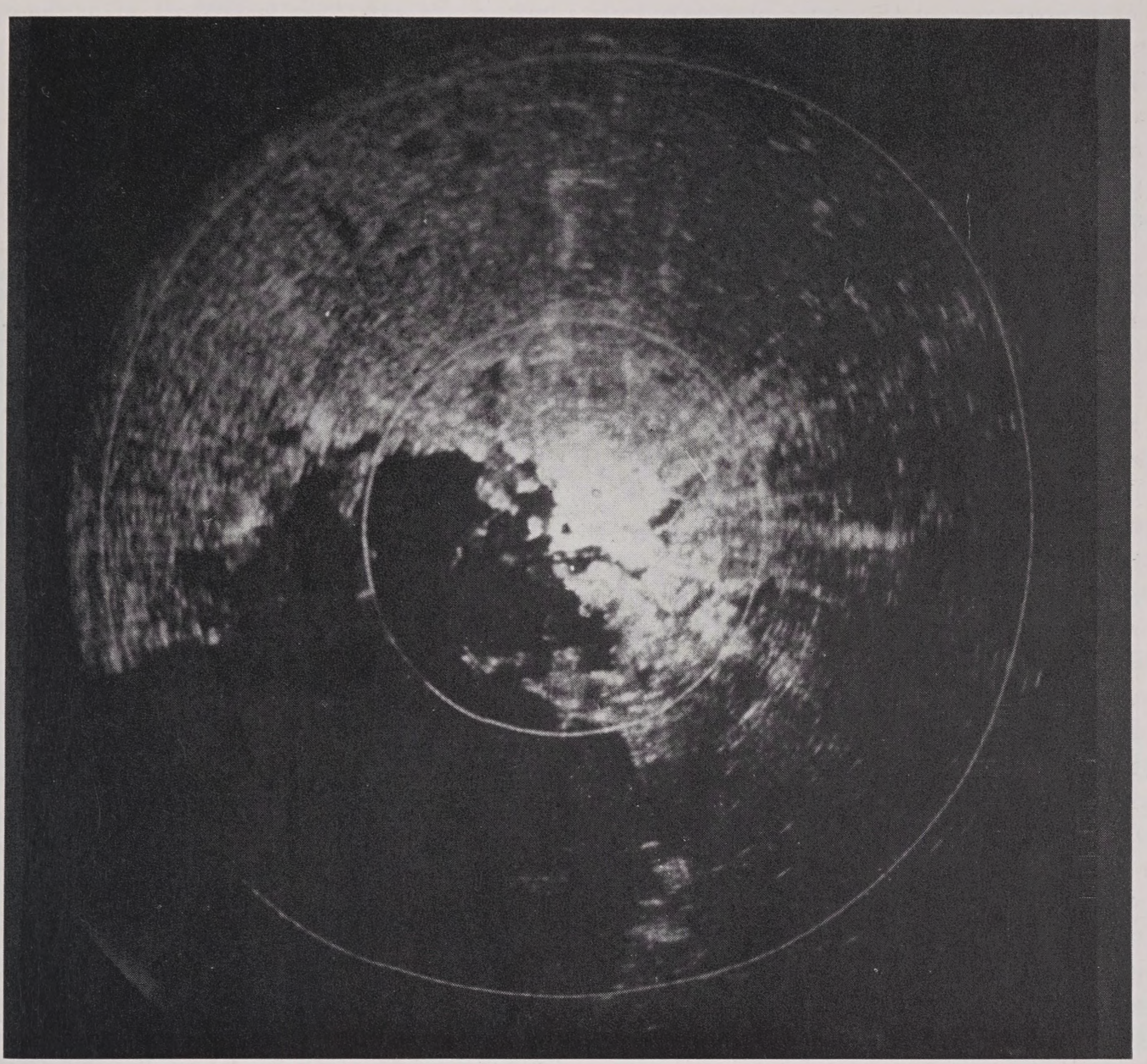


FIGURE 4B. Radar presentation similar to Figure 4A with improved antenna.

4B shows a similar picture with this type of distortion removed by an improved antenna design.[40]

The two pictures in Figure 4 illustrate still another distortion that can be introduced by the vertical antenna pattern. It will be noted that in Figure 4A the signal from terrain almost below the airplane is more fuzzy in appearance than similar signals in Figure 4B. This occurs wherever the beamwidth grows wider at steeper angles. However, modern design permits the constructions of antennas which have a beamwidth independent of angle of depression (see Figure 4B).

DISTORTION ARISING FROM THE MOTION OF THE AIRPLANE

The radar map is not an instantaneous radar picture of the terrain below the airplane but rather depends on the persistence of the echoes on the PPI to present a continuous picture. Frequently 3 sec or more are required to complete one scan of the radar antenna, i.e., through 360 degrees, and during this time an aircraft, traveling with a ground speed of 180 mph, will move 0.15 mile. The resulting spiral distortion of the radar map is difficult to analyze and sets a limit on the accuracy with which the position of the airplane may be established from the radar map. Remedies for this distortion are the use of sector scanning and increased scanning speed. A recent laboratory development (rapid scan radar) completely overcomes the spiral distortion caused by the airplane motion and effectively gives a radar motion picture of the terrain beneath the aircraft. The rapid scan radar uses a short persistence PPI and a scanning rate of 720 scans per min. Another advantage of this type of instantaneous display is a feeling of reality of the motion of the aircraft over the earth that is conveyed to the radar observer. It is similar to looking out the nose of the airplane at the terrain below.[34]

Aside from its translational motion, an airplane may also pitch and roll. In such cases the antenna may be pointed down at the ground in one part of its scan and up into the sky at another. This means that the range displayed in one portion of the radar map will be limited. This washing out of radar signals on a turn is very objectionable, since the turn at the *initial point* [IP] of a bombing run is always a turn toward the target. Therefore, the antenna looks toward the ground in the target direction and the radar operator must wait until the turn is completed before he can relocate the target. Moreover, any sharp turns to avoid antiaircraft fire will also cause the operator to lose the target.

The solution for these difficulties is the stabilization of the antenna system so that it maintains the same orientation with respect to the ground irrespective of the movement of the airplane. The reader is referred to the bibliography [54] for a discussion of the relative merits of the various ways in which this can be done. (See also Section 4.1.3.) The importance of some form of antenna stabilization for radar mapping systems used for bombing cannot be stressed too strongly. A further complication is that the azimuth data obtained from the scanner may not be correct during a roll (or bank) of the aircraft. It is therefore desirable that corrections be made to the azimuth information transmitted to the PPI.

Distortion from System Errors

In addition to the inherent types of distortion just described there are many types of errors that can be introduced by imperfect radar systems. Some of these are nonlinear PPI sweep speeds, imperfect PPI display stabilization, and irregularities in the start of the PPI sweep trace. The most important of these is imperfect display stabilization. The weak point of all radar mapping systems is the fidelity of reproducing the azimuth of the reflecting objects. Although the range can be measured with high accuracy, the angular position in the radar map may differ from the actual bearing by as much as 3 degrees in a common radar mapping system (AN/APS-15).

In general, the radar display is coupled to the compass in the aircraft so that the top of the radar map corresponds to North. Therefore, for true angular reproduction, both the antenna-PPI and the compass-PPI servomechanisms must be exact follow-up systems. Considerable attention should be devoted to this part of the navigational or bombing radar design, since the position of an airplane is most easily established by a measurement of the range and the bearing of an identified landmark on the radar display.

Conclusion

Several of the more common types of distortion of radar maps have been discussed which have a direct bearing on the bombing problem, particularly where identification of targets is concerned. Since the difficulty of radar target identification has borne the brunt of criticism for the general inaccuracy of radar bombing, radar map distortion should be minimized in the design of any new radar bombing system.

7.2.2 Other Design Considerations of Radar Bombing Systems

The two most important requirements for radar mapping systems to be used for bombing are an accurate radar map of the terrain beneath the aircraft and a means for accurately determining the range of the target. Other design considerations may be divided into three groups, namely, factors affecting (1) radar range, (2) radar displays, and (3) convenience of operation.

Factors Affecting Radar Range

Microwave radar systems are, in principle, limited in range by the horizon, no matter how powerful their transmitter or how sensitive their receiver. The horizon range in statute miles is approximately equal to the square root of twice the altitude in feet of the radar set, assuming that the reflecting objects are at sea level. Thus for an altitude of 20,000 ft, the horizon distance is 200 statute miles.

However, because of the rigid restrictions on weight and input power of airborne installations, most airborne radar systems are limited in range not by horizon distances, but rather by insufficient power output and antennas of reduced size. Under these circumstances if we assume that the scanner is pointed continuously at the target and that there is no atmospheric absorption or refraction, the maximum range ($R_{\max}$) is given by:[51b]

$$R_{\max} = \left(\frac{PG^2\lambda^2\sigma}{64\pi^3 p_{\min}}\right)^{\frac{1}{4}} \tag{1}$$

where P = peak power of transmitted microwave pulse,

$p_{\min}$ = power of smallest signal that can be detected by the radar receiver,
G = antenna gain along center of radar beam relative to an isotropic radiator,
λ = wavelength of transmitted radiation,
σ = effective cross section of the reflecting object.

It would seem from equation (1) that greater range performance could be obtained by increasing the wavelength (λ). This is not true, however, because the antenna gain G decreases with increasing wavelength λ. Thus for a paraboloid of revolution with a dipole at its focus, which was a very common type of radar antenna, G is equal to 2.4 ($\pi A/\lambda^2$), where A is the area of the paraboloid aperture (see also Section 15.1.3). For this value of G, equation (1) becomes

$$R_{\max} = \left(0.36\,\frac{P}{p_{\min}}\,\frac{A^2\sigma}{4\pi\lambda^2}\right)^{\frac{1}{4}}. \tag{2}$$

The above analysis applies in particular to a searchlight type of beam rather than a cosecant-squared beam that provides uniform echo signals irrespective of range out to the maximum range $R_{\max}$. In the latter case, which was mentioned under "Distortion Caused by Unsatisfactory Antenna Patterns," Section 7.2.1, the role of the vertical height of the antenna in determining maximum range is comparatively minor; the vertical aperture is adjusted to reduce the difference between the actual and the cosecant-squared pattern rather than to concentrate the energy into a more and more narrow beam. As a consequence, although equation (1) remains true if G represents the gain at the nose of the beam, the relation between G, λ, and the dimensions of the antenna must be modified.[51b]

For a cosecant-squared beam antenna having an effective horizontal width d, the maximum gain G is equal to $(4\pi/\sin\theta_0\cos\theta_0)(d/\lambda)$. Here, θ_0 is the angle of depression of the nose of the beam and is given, in terms of the altitude h and the slant range R of the beam nose, by the relation $\sin\theta_0 = h/R_0$. The maximum gain of this antenna is equivalent to that of a uniformly illuminated aperture of length d and height $\lambda/\sin\theta_0\cos\theta_0$. As a result of these relationships the radar equation (1) becomes:[51b]

$$hR_0\cos\theta_0 = \left(\frac{P}{p_{\min}}\,\frac{\sigma}{4\pi}\,d^2\right)^{\frac{1}{2}}. \tag{3}$$

Thus, the inverse relationship between maximum range and altitude when working with a cosecant-squared beam is evident, as is the fact that the choice of wavelength will have only indirect effects upon the range performance through the variation with wavelength of such factors as σ and $p_{\min}$. (For ground painting and extended complex targets, it is reasonable to suppose that σ would vary directly with the width of the radar beam.) It is also interesting to note that, for constant altitude, the maximum range for which such coverage can be provided varies as the *square root* rather than as the *fourth root* of the transmitter power, so long as the antenna keeps the cosecant-squared pattern.

In the following paragraphs the variation of maximum range with several factors will be considered:

Wavelength. As seen in Section 7.2.1 under "Inadequate Azimuth Resolution," a decrease in wavelength increases the azimuth resolution of the radar set, so it would seem advisable to use the shortest possible wavelength of radiation. Unfortunately, most radiation with wavelengths less than 1.5 cm is highly attenuated by rain, water vapor, and molecular absorption[51] in the lower levels of the atmosphere. Moreover, the generation of large amounts of microwave power at these frequencies and the design of satisfactory circuit components introduces additional difficulties.

In such circumstances, a compromise must be made between increased resolution and sufficient range. With the advent of high-speed bombers having velocities such as 600 mph, the maximum range at which a target can be identified becomes very important if any corrections are to be made in the course of the airplane on the bombing run. On the other hand, the use of improved navigational devices may make some sacrifice of maximum range acceptable in exchange for a marked improvement in resolution. Because of this, future radar design may use wavelengths of 8 or 9 mm which occur in the dip in the absorption curve between the water vapor absorption peak near 1.3 cm and that for oxygen at 0.5 cm.[51b] (For short-range communication systems, on the other hand, strong exponential absorption might be desirable for security and freedom from interference.)

Output Power. Increasing the output power or increasing the receiver sensitivity are the other obvious methods of extending the usable radar range, since the maximum area of the antenna is fixed by aerodynamic considerations. Here, however, to double the maximum range, the output power must be multiplied by at least 4 for a shaped beam, by 16 for a searchlight-type scanner, and by an even greater factor if appreciable absorption is present. The effect is, of course, a resultant increase in the size and weight of the radar system.[51] Receiver sensitivity affects the maximum attainable range in an analogous way, i.e., to increase the maximum range, the value of $p_{\min}$ would have to be reduced by the same factor that P would have to be increased. The maximum range is much more dependent on antenna size, but increasing this quantity usually introduces practical difficulties.

Scanning. Equation (1) was developed on the assumption that the antenna was pointed directly at the reflecting target so that the target was continuously illuminated. If the antenna is scanning, however, a reduction in the observed maximum range is at once apparent. This is to be expected, since the number of pulses of microwave energy that illuminate the target will be dependent on the speed with which the antenna scans over the target.

Since the intensity with which the returning echo is portrayed on the radar map varies greatly with the number of pulses received and since the eye of the observer is similarly influenced, a reduction in the number of returned pulses has a damaging effect on the maximum range at which echoes can be detected. For a further analysis of this phenomenon see Chapter 15 and the R. L. Technical Series.[51]

The reduced echo intensity caused by scanning is of particular interest to bombing radar systems because the many advantages of a continuous presentation of any rapid scan system must be weighed against the disadvantage of reduced maximum range. Sector scanning is one method of reducing the scanning loss. It is also obvious that the loss will be greater for narrower beams, since fewer pulses per scan can be observed, so the loss must be balanced against the increased antenna gain G that results from the use of a narrower beam.

Receiver Noise Figure. As already noted, improved performance of radar sets can be obtained by increasing the sensitivity of the radar receiver. However, $p_{\min}$ has a minimum value below which it is theoretically impossible to go. This minimum value is the noise signal caused by thermal agitation of electrons in the input circuits of the radar receiver.[51] In actual systems, the amount of receiver noise present is still greater than this theoretical lower limit. Thus the overall noise figure, which is the ratio of the actual noise to the theoretical noise, was about 50 (17 db) for radar receivers of 3.2 cm wavelength radiation in 1942, and had been reduced to 20 (13 db) for systems in service in 1945. A further reduction in noise figure to 10 (10 db) is possible with 1945 laboratory techniques. This means that the sensitivity of receivers for wavelengths in the 3.2-cm region can be increased at most by a factor of 10, with a resulting increase in maximum range of no more than 2 or 3. Increasing the receiver sensitivity is perhaps the most desirable method of getting increased range for airborne radar systems, since only a slight burden is put upon the installation weight, size, and power requirements of the equipment. On the other hand, increased sensitivity will make the radar, when used for bombing, more vulnerable to radar countermeasures.

Receiver Bandwidth. The receiver noise caused by thermal agitation of electrons is directly proportional to the receiver i-f bandwidth, so that a reduction in the i-f bandwidth will result in an increase of receiver sensitivity. However, the pulse transmitted and received by the radar system is composed of a spectrum of frequencies which must all pass through the i-f amplifier, if the receiver output pulse is to be a sharp, distinct replica of the input pulse. If this condition does not hold because the i-f bandwidth is too narrow, some of the higher frequency components of the pulse will be missing and a poorly defined pulse will result, with a corresponding reduction in range resolution (see "Inadequate Range Resolution," Section 7.2.1).

The engineering compromise which yields the lowest values of $p_{\min}$ that is consistent with good pulse reproduction is the use of an i-f bandwidth equal to $(1.2/\tau)$ megacycles, where τ is the pulse duration in microseconds. This value is not a critical one, since for bandwidths twice or half as great as the optimum value the change in receiver sensitivity is only 15 per cent.

Pulse Length, Sweep Speed, and Recurrence Frequency. The receiver sensitivity is also indirectly dependent on the duration of the microwave pulse (τ). $p_{\min}$ is inversely proportional to τ provided the receiver bandwidth is always adjusted to the optimum value and if the distance covered by the sweep during the emission of the pulse is kept constant. For the sweep speeds commonly employed, an increase of sweep speed will affect the minimum detectable signal $(p_{\min})$ favorably. Accordingly, for slow sweeps, with the sweep speed and recurrence frequency kept constant, an increase of the pulse duration by a factor α and a corresponding decrease of bandwidth can result in dividing $p_{\min}$ by the quantity $(\alpha)^{3/2}$ and is equivalent to increasing the peak transmitter power by this same factor. A decrease of recurrence frequency by a factor α, that would be required in the above example if the average power is to be kept constant, may affect the sensitivity adversely by a factor of $\alpha^{-\frac{1}{2}}$, so that the net gain in the case cited would be roughly a factor α. For this reason provision has been made for a 5-μsec pulse on several recent airborne radar systems as an aid in long-distance search. However, as such long pulses have very poor range resolution (see Section 7.2.1, "Inadequate Range Resolution"), shorter pulses must also be provided for precision mapping.

Miscellaneous Factors. As is evident from the above discussion, there are many factors which may affect the maximum range of a radar system and some, such as the characteristics of fluorescent screen materials, will not be described here. It should be emphasized that the material presented in this section concerning the basic design considerations of a radar system is by no means complete, and the reader is referred to the Radiation Laboratory Technical Series [51] for a more complete treatment.

Radar Displays

Other Types of Radar Mapping Presentation. Most frequently, the PPI type of radar mapping (see Section 7.2.1) is used for radar bombing, but some systems, particularly for marine work, have employed the type B display and variations of the B display. The B display is a square radar map wherein target range is plotted vertically as the y coordinate and azimuth is plotted horizontally as the x coordinate. Ordinarily, less than 180 degrees of azimuth are portrayed in a B type map.

The type B radar map becomes severely distorted as the target moves in toward the airplane, which is apparent from the fact that the point under the plane is displayed as a line. However, for killing drift on a bombing run, the type B display is especially helpful, since any deviation from a constant azimuth is very noticeable and resulting corrections in the airplane's course will be made earlier and more rapidly. For over-land bombing, however, where the identification problem is severe, an auxiliary PPI is essential.

Another type of radar display frequently encountered is the delayed PPI. Although the slant range distance displayed on the PPI may be only 15 miles, the start of the sweep may be delayed in fixed steps of 10 miles out to as much as 200 miles. The resulting display is severely distorted but the expanded range scale permits very accurate range determination. For this reason, the delayed PPI is reserved for use with beacons, where it is important to determine the ranges to beacons very accurately.

Many other modified radar displays have been devised for special purposes, but a complete listing of these will not be undertaken here. Of special interest is the scheme now employed in the British H2S Mark IVa radar wherein the terrain features appear to remain fixed in the display while the origin of the sweep, which corresponds to the airplane, moves about on the fixed radar ground map. Separate controls are used to position the area being mapped.[33]

Three-Tone PPI Presentation. As seen in Section 7.2.1, "PPI Spot-Size Distortion," the output signals from radar receivers are limited to prevent blooming of the spot size on the radar PPI. This limiting provision has a particularly harmful effect upon the region of signal strength that can be portrayed on the radar map. Thus if the receiver gain is increased so that land-water boundaries are visible, the stronger echoes from the built-up areas will blend with those from the land. On the other hand, if the strong land echoes must be differentiated from the very strong echoes from built-up areas, a reduced receiver gain must be used in which the land-water contrast is entirely lacking. This makes it very difficult to locate built-up areas such as factories by reference to some nearby river or lake.

Electronic devices known as three-tone circuits were devised to overcome this difficulty and it is now possible to present built-up areas against a fainter background of land in which the water areas appear black. Figures 4A and 4B show the improvement in identification that is possible by using such a three-tone attachment. For details of the method of securing this desired effect, the reader is referred to the bibliography.[49a,51c]

Factors Affecting Convenience of Operation

The ideal radar set would have only one control, an on-off switch. Unfortunately, radar systems used for bombing are not so simple, since the job to be performed is complicated and flexibility is sometimes desired. As a consequence, a number of controls must be used and the resultant complexity of the radar set makes it necessary to train radar operators for a considerable period of time. A sizable reduction in the training program could be obtained, however, if more attention were given to the design of simplified automatic controls. A few such improvements follow.

1. Completely *automatic frequency control* [AFC] so that the operator does not have to tune in manually either the echo or the beacon signal. A combined mapping and beacon presentation is also possible.
2. Optional fixed range marks, preferably showing ground range.
3. A continuously variable range mark with an associated dial for use in reading the precise range to identified landmarks.
4. An electronic cursor for measurement of angles to the identified landmarks. As in the case of Nosmo (Section 8.3.2), this cursor could be either bright or dark.
5. Ganged controls so that sweep speed, pulse duration, pulse recurrence frequency, i-f bandwidth, and range-marker interval would all be shifted by one control. This feature has been incorporated into the AN/APS-33 radar system.

The desirability of a simplified control system is readily apparent. It may be hoped that the progress of radar will be like that of radio, where a pushbutton has replaced the minimum of three dials previously required to tune in a radio station. The general radar experience of World War II has shown that the increased performance which a number of controls may provide in the hands of experts is far outweighed by the maladjustment that a confused operator can devise. Thus, it is much more desirable to accept a known reduction in performance in order to simplify the control process than to gamble on the correct adjustment of a larger number of controls that may provide a higher performance.

7.2.3 Brief Description of Several Radar Mapping Systems

The systems described below are offered as a selection from existing equipments illustrating the basic design principles of the two preceding sections. They include systems with considerable field service as well as recently developed laboratory prototypes, so that trends can be observed. The listing is in chronological order of development and includes only developments made in the United States. Attention is given in this outline chiefly to mapping functions. See Table 2 for a brief listing of some fundamental design parameters.

1. ASB-3. This is an early search and homing radar, operating at 50 cm. Because of the relatively wide beam, no automatic scanning provision is provided, the antenna array being manipulated by hand. The indicator is a modified A scope. Land masses to 70 miles and large ships to 30 miles are standard performance.
2. AN/APS-3. This Navy X band radar, which has seen abundant field service, is designed for use at medium and low altitudes (500 to 10,000 ft). It has a sector type of scan with a B scope presentation. Ranges of 80 nautical miles on single freighters have been commonly attained.
3. AN/APS-15. This is an X band radar system provided with two alternate antennas: one providing a cosecant-squared pattern suitable for use at high altitudes (10,000 to 36,000 ft); the other antenna, of higher maximum gain, provides a cosecant-squared pattern suitable for low altitude use (500 to 10,000 ft). With this equipment, which has seen field service in great numbers, particularly with the 8th AAF in

TABLE 2. Design characteristics of some existing radar systems

	AN/APS-15	AN/APQ-7	AN/APS-34	AN/APS-33	Cadillac	AN/APQ-13 with large antenna	K band rapid scan
λ (cm)	3.22	3.22	1.25	3.22	10	3.22	1.25
G	800 or 1,200	1,500	4,000	1,350	1,150	1,130	4,000
P (kw)	40	50	30	100	1,000	35	24
d (in.)	29	190	29	29	96	60	29
τ (μsec)	1 or 0.5	0.75 or 0.4	0.5 or 0.25	0.5, 5.0	2	0.5, 1.13	0.16
ν_r (pulses per second)*	650 or 1,010	400 or 1,600	800 or 1,600	800, 200	300	1,350, 624	6,000
Beamwidth (degrees)	3	0.4	1.0	3.0	3.5	1.3	1.0
Typical installation	Ventral	Special housing	Ventral	Ventral	Special housing	Ventral	Ventral
Scan type (degrees)	360 or sector	± 30	360 or sector	360 or sector	360	360 or sector	360

*The lower value of νr is used with the larger value of τ. Most of the radars here described also have a 2-μsec pulse and a suitable recurrence frequency for beacon interrogation.

England, land mapping can be done to 40 nautical miles, using the high-altitude antenna, and large cities can be seen at 90 miles.

4. AN/APQ-7 (Eagle). This Army equipment which has been in limited field service, is designed as a high-resolution radar system. It is intended primarily for high altitude use (25,000 ft). The antenna is a 16-ft linear array of dipoles housed in a special wing-like nacelle. Scanning is done by an electrical method which does not require the dipole array to be rotated. Ranges up to 160 miles have been obtained on cities. Although giving very superior resolution, the system suffers somewhat from the inconvenience of the large antenna array and its inability to scan outside a 60-degree sector centered about the forward direction.

5. AN/APS-34. This Navy K band radar, which went into production in 1945, is designed for high-resolution search from medium altitudes (1,000 to 10,000 ft). Since the operating wavelength of 1.25 cm is virtually that for maximum absorption by water vapor, the range of this equipment is limited by the resulting attenuation. On a dry day near Boston (4–5 gm H_2O per m^3) there is land mapping to 20 miles. On a moist day (15 gm H_2O per m^3) this may be reduced to 7 or 8 miles. Boston has been seen at 35 nautical miles during dry weather. The resolution is very good.

6. AN/APS-33. This Navy X band radar is designed to supplant the AN/APS-15 for medium- and low-altitude search functions. The use of a long search pulse (5 μsec) with r-f band switching and other improvements permits land mapping to about 100 nautical miles. Large cities have been seen at the horizon (120 miles) at 12,000 ft.

7. Cadillac. This radar system is essentially in the early production stages (1945). It is a Navy S band high-power system designed for search and special uses at medium to high altitude (10,000 to 30,000 ft). Land mapping to 120 miles is obtained and ranges on large ships are usually limited by the horizon. Cities can be seen at 200 nautical miles.

8. AN/APQ-13 with Large Antenna. The AN/APQ-13 is an Army equipment similar to the AN/APS-15. For high altitude operation in large aircraft, this basic equipment was modified by the addition of a 60-inch antenna. The aim was to provide a high-resolution system with as small a protrusion of the antenna housing below the aircraft fuselage as possible. Painting of land is obtained to 70 miles at 20,000 feet and 35 miles at 5,000 feet. The antenna protrudes only 7 in. below the keel line of the aircraft.

9. Rapid Scan. The Rapid Scan system is a K band development of the Radiation Laboratory which was in the laboratory stage at the cessation of hostilities of World War II. It produces a very high-resolution display at 720 scans per min on a very short persistence cathode-ray tube. Although the range is limited by water vapor attenuation, it embodies a novel idea in design which will be very useful where very fast moving aircraft are involved. The reported land mapping range is about 9 miles on a dry day but will probably be improved.[31]

An examination of Table 2 shows that the trend in airborne search radars is toward higher power, narrower beams, antennas giving more uniform ground coverage, longer pulses for long-range search and mapping, and shorter pulses where good discrimination is required.

7.3 ACCURATE RADAR RANGE MEASUREMENT

7.3.1 Principles of Airborne Radar Ranging

Basically, all radar range measurements are made by measuring the time required for a radar pulse to travel from the radar transmitter to a reflecting object and back to the radar receiver. The total distance traveled by the radar pulse will be equal to the product of the elapsed time by the speed of light, and the range to the reflecting object will be one-half that distance, or approximately 490 ft per μsec. Range marks can be produced by applying a signal to the indicator at certain predetermined times after each pulse is emitted from the radar transmitter. Such range marks will appear on a PPI as concentric circles.

The range of any reflecting object may be determined by comparing its position on the PPI with the position of one or more range marks. For navigational purposes, interpolation between fixed range marks representing range intervals of 1, 5, or 10 miles is usually adequate, but more convenient and more accurate methods are usually required for use with bombing computers. For the latter purpose, a variable range mark is usually employed and its accuracy should be consistent with the resolution of the radar presentation, i.e., the error in measuring

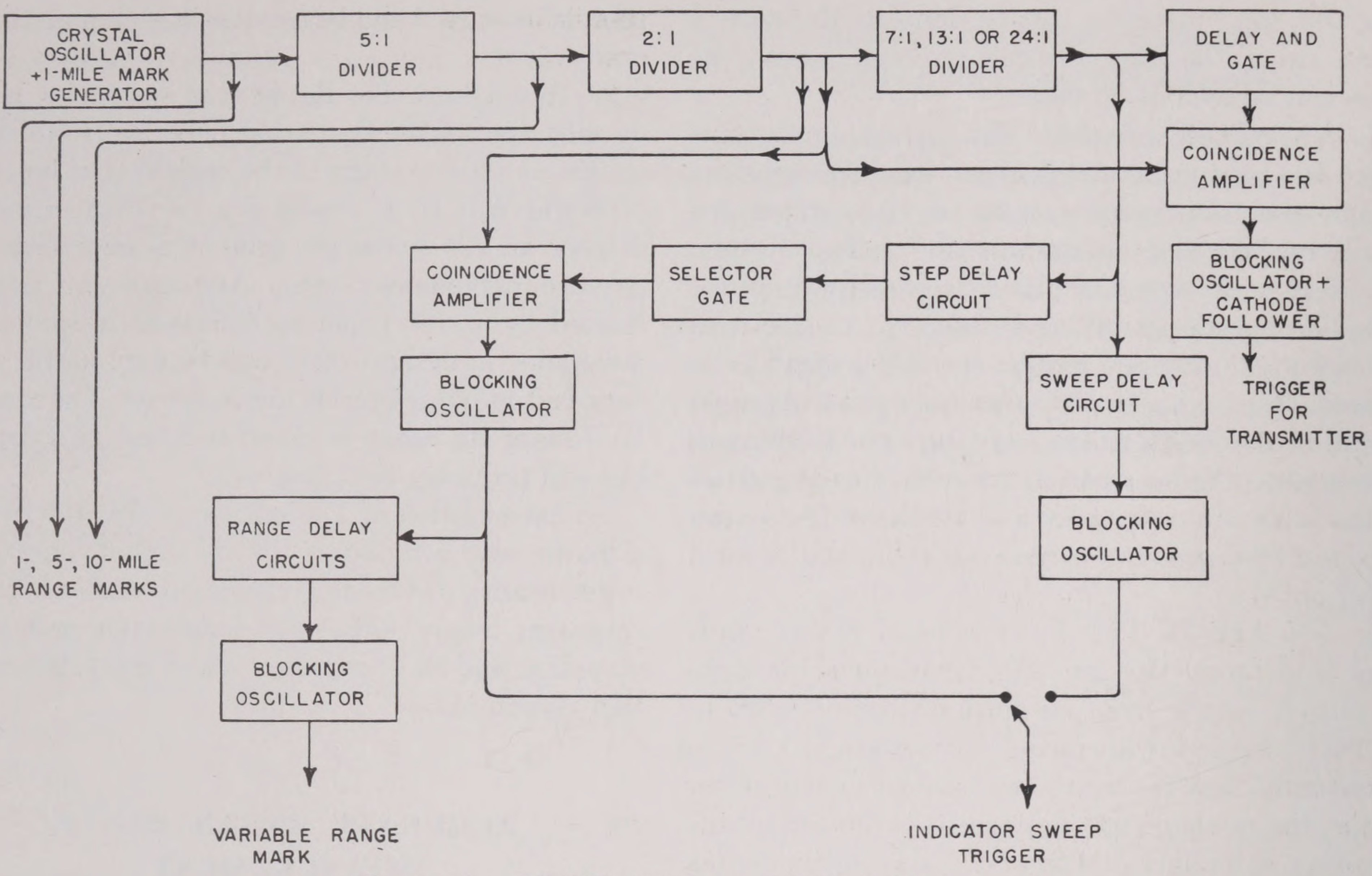

CRYSTAL OSCILLATOR +1-MILE MARK GENERATOR
5:1 DIVIDER
2:1 DIVIDER
7:1, 13:1 OR 24:1 DIVIDER
DELAY AND GATE
COINCIDENCE AMPLIFIER
BLOCKING OSCILLATOR + CATHODE FOLLOWER
TRIGGER FOR TRANSMITTER
COINCIDENCE AMPLIFIER
SELECTOR GATE
STEP DELAY CIRCUIT
BLOCKING OSCILLATOR
SWEEP DELAY CIRCUIT
BLOCKING OSCILLATOR
1-, 5-, 10- MILE RANGE MARKS
RANGE DELAY CIRCUITS
BLOCKING OSCILLATOR
VARIABLE RANGE MARK
INDICATOR SWEEP TRIGGER

FIGURE 5. AN/APS-15A range unit block diagram.

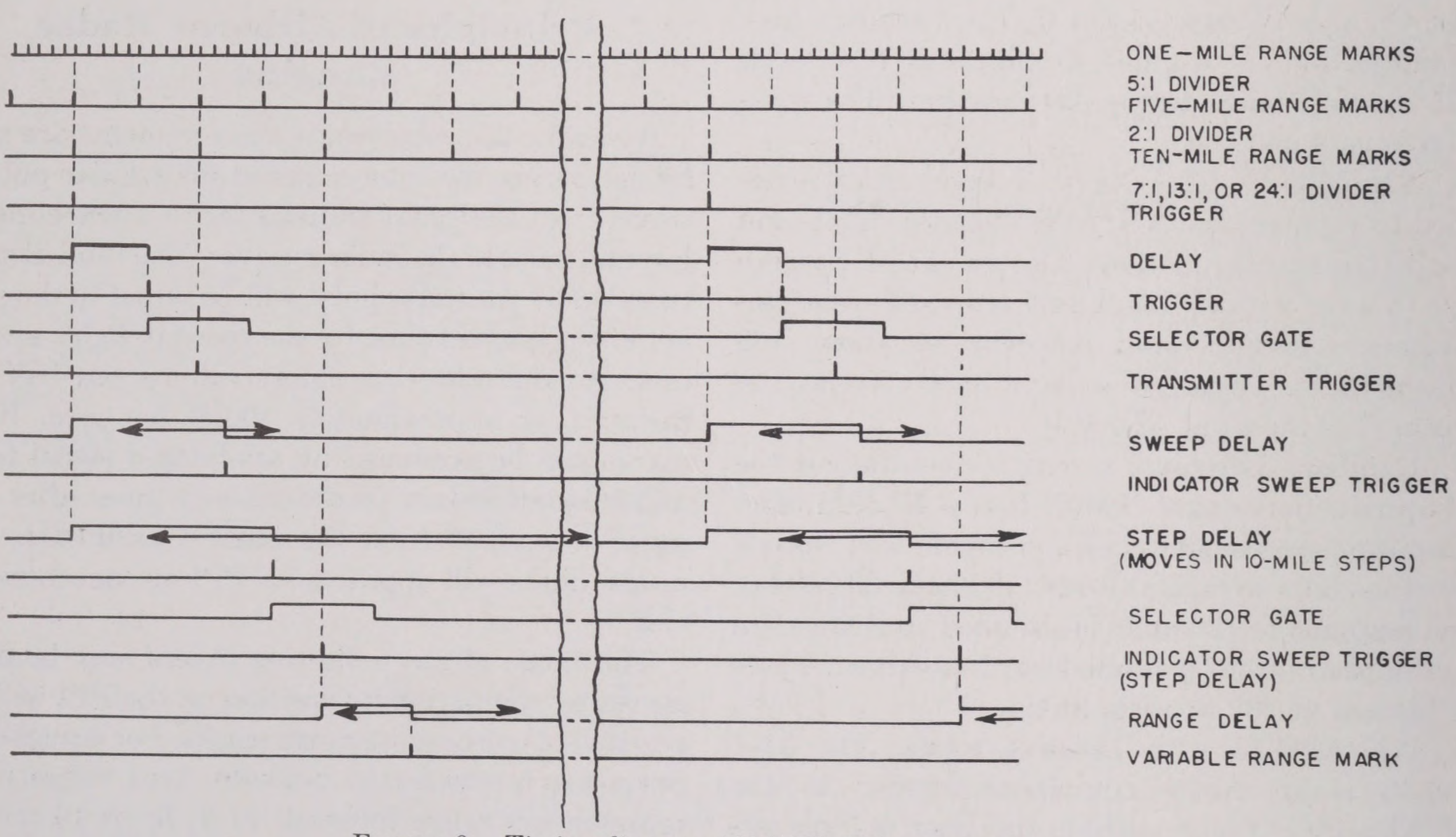

ONE-MILE RANGE MARKS
5:1 DIVIDER
FIVE-MILE RANGE MARKS
2:1 DIVIDER
TEN-MILE RANGE MARKS
7:1, 13:1, OR 24:1 DIVIDER
TRIGGER
DELAY
TRIGGER
SELECTOR GATE
TRANSMITTER TRIGGER
SWEEP DELAY
INDICATOR SWEEP TRIGGER
STEP DELAY (MOVES IN 10-MILE STEPS)
SELECTOR GATE
INDICATOR SWEEP TRIGGER (STEP DELAY)
RANGE DELAY
VARIABLE RANGE MARK

FIGURE 6. Timing diagram AN/APS-15A range unit.

slant range should be appreciably smaller than the distance corresponding to the range resolution of the radar equipment.

For a description of circuits for producing fixed and variable delays suitable for measuring radar ranges, consult the bibliography.[48e, 51] The present discussion includes a brief description of the range unit of the AN/APS-15A radar bombing equipment and an examination of some of the problems associated with its use.

7.3.2 Description of a Typical Range Unit (AN/APS-15A)

The range unit of an airborne radar bombing system usually serves as the timing or synchronizing device for the entire system. As such, it may determine the pulse recurrence frequency and indicator sweep timing, as well as provide the delay circuits for range measurements. This is true for the AN/APS-15A range unit, as may be seen from the block diagram of Figure 5 and the timing diagram of Figure 6.

A crystal-controlled 80.86-kc oscillator is the basic timing circuit from which all the triggers and range markers of the AN/APS-15A range unit are derived. The period of oscillation corresponds to 1 nautical mile of radar range and is used as a standard for the calibration of the variable delay circuits, as well as to form the fixed range marks and the synchronizing pulses for the transmitter and indicator units. One-mile range marks are generated by differentiation of 80.86-kc square waves produced from the output of the crystal-controlled oscillator. From these, a 5/1 divider produces 5-mile range marks and, similarly, 10-mile range marks are created with a 2/1 divider circuit. An additional divider circuit, whose dividing ratio can be adjusted to 7/1, 13/1, or 24/1, produces a *trigger* with resulting recurrence frequencies of 1,155, 622, or 337 pulses per second, which are used with transmitted pulse durations of 0.5, 1.0, or 2.0 μsec respectively. The last-mentioned trigger activates three other circuits: (1) a fixed-delay circuit followed by a gate which selects the next 10-mile range mark, which in turn is used to trigger the transmitter; (2) a variable-delay circuit which initiates a trigger for starting the indicator sweeps at a time corresponding to from 6 miles before the transmitter pulse to 6 miles after the transmitter pulse; and (3) a step-delay circuit, variable in 10-mile steps, followed by a gate which selects any 10-mile range mark before the next transmitter trigger for use as an alternate indicator-sweep trigger. The 10-mile mark selected by the step-delay circuit is also used to trigger the variable range-delay circuit which produces the variable range mark used for bombing.

In summary, the range unit described above provides a trigger for the radar transmitter; a trigger for the indicator sweeps which may either be timed within the range of 6 miles before and 6 miles after the transmitter trigger, or delayed in steps of 10 miles each up to 200 miles after the transmitter trigger; crystal-controlled range marks of 1-, 5-, and 10-mile intervals; and a range mark which is variable from 0.5 to 15 miles in range and which may be delayed in steps of 10 miles by the step-delay circuit for the indicator sweeps. The crystal-controlled range marks may be used to calibrate the variable-range mark.

In addition to the intentional delays introduced by the circuits discussed above, circuits in the range unit and other components of the radar system introduce additional unintentional and, in most cases, undesirable delays which must be considered when calibrating the range unit for bombing purposes.

7.3.3 Problems of Range Calibration

As mentioned in Section 7.3.2, several characteristics of the AN/APS-15A range unit as well as of other units of a complete bombing radar system must be considered when calibrating the range circuits for bombing purposes. Most of these characteristics would be encountered in other equipments of the same general type and are therefore of general interest.

The problem of matching a range mark with a signal is, to a certain extent, an ambiguous one which depends upon many factors, including the judgment of the operator and the adjustment of the equipment. The calibration adjustments of the range delay circuit are a *slope adjustment* and a *zero adjustment.* The variable range mark is permanently connected to the A scope, where it may be compared with the crystal-controlled 1-mile range marks. Coincidence of the variable range mark and a 1-mile mark may, with care, be established with a reproducibility of about 25 ft.

Making the slope adjustment is quite simple, since it is necessary only to select two 1-mile marks between 1 and 15 miles in range and adjust for the proper difference in range-scale readings when the variable range mark is made coincident with the selected 1-mile marks. The particular 1-mile marks chosen for this purpose should be those for which the slightly nonlinear characteristic of the range delay circuit causes the least maximum deviation over the ranges of particular interest to the bombing method used.

The zero adjustment is considerably more complicated than the slope adjustment, and the remainder of this section will be devoted to a discussion of factors which influence the setting of the zero control.

One important consideration is the criterion for matching the range mark to a signal on the PPI. The range marks are not instantaneous and therefore have a finite width on the PPI; moreover, their wave shape is not rectangular but the sides are sloping, making an evaluation of their width difficult. Most operators prefer to have the outer edge of the range mark just touch the inner edge of the signal when making an accurate range measurement. Under ideal conditions, this would occur when the half-voltage point on the tracking edge of the range mark is coincident with the half-voltage point on the leading edge of the signal pulse. The finite spot size of the PPI requires that the range mark and signal be slightly more separated than under ideal conditions. The magnitude of this effect increases as the brilliance of the PPI presentation is increased, and is greater for slower PPI sweep speeds, which correspond to longer-range sweeps. For the latter reason, the sweep speed used during a bomb run should preferably be constant. If a presentation where the target remains in a fixed position on the PPI is desired, this should be accomplished by a variable offset-center presentation rather than by automatic sweep expansion. A thin, sharply defined range mark is highly desirable, but to achieve this, the circuit through which the range mark passes must have a wide bandwidth.

The crystal-controlled 1-mile range marks indicate slant range intervals of 1 mile, but because of unintentional circuit delays, they do not represent slant ranges which are exactly integral numbers of miles, that is, a zero error exists. The 1-mile range mark which nominally represents zero range arrives at the indicator after a small amount of delay caused by isolating and impedance matching circuits and by the video amplifier of the receiver. This same 1-mile range mark, after some delay in the 5/1 and 2/1 divider circuits, becomes the 10-mile range mark which is selected as the trigger for the transmitter. Further delay occurs in isolating and impedance matching stages and in the transmitter itself.

The transmitted pulse is delayed (as are radar return signals) in the receiver before it reaches the indicator. The appearance on the PPI of the leading edge of the transmitted pulse may be considered as representing a signal of zero range, and the interval between the trailing edge of the reference 1-mile range mark and the leading edge of the transmitted pulse may be considered the zero error of the crystal-controlled range marks. If the zero delay is known, the 1-mile range marks can be used to calibrate the variable range mark.

If we denote (1) the delay between the generation of the zero range mark and the appearance on the PPI of its leading edge by d_1, (2) the delay between the generation of the zero range mark and the appearance of the leading edge of the transmitted pulse by d_2, and (3) the width of the range mark by w, then the zero delay is $(d_2 - d_1 - w)$. All three of these quantities are subject to variation if the vacuum tubes or certain other elements of the associated circuits are changed, or if the characteristics of these elements change with time. The quantity d_2 varies with the setting of the i-f gain control of the receiver and w changes with variations in range mark amplitude and PPI bias.

The most effective means of determining the zero error of such a radar ranging system is to calibrate the variable range mark by means of the radar return from an object at a known distance from the radar antenna. If this is done, the same adjustments of PPI sweep speed, PPI bias, signal intensity, and range mark intensity that would be employed in normal operation should be used. Unfortunately, this calibration procedure is inconvenient and, in the case of H2X operations in Europe, was used only with a few "sample" equipments to determine an average value of zero error which was then used to calibrate the many sets used in bombing missions.

An alternate method of zero calibration uses a delayed sweep to compare the variable range mark with the next transmitted pulse. This may be accomplished by using the step delay to start the PPI sweep and the range-delay circuit just 10 miles before the next transmitter trigger is selected. With the range scale set to 10 miles, the zero adjustment is so made that the outer edge of the range mark just touches the inner edge of the circle on the PPI caused by the transmitted pulse. Three objections to using this method to calibrate the AN/APS-15 range unit were: (1) the sweep speed must be relatively slow (greater than 10 miles in range) in order to display the transmitted pulse; (2) the position of the transmitted pulse on the PPI may vary as much as 150 ft with extreme variation in receiver gain adjustment; and (3) the leading edge of the transmitted pulse was often obscured by the leakage of trigger pulses into the receiver circuits. In spite of these objections, this method of calibration is easily performed and is often used whenever the resultant errors can be neglected.

From the foregoing discussion, it is clear that very accurate range measurements by radar cannot be made without accurate calibration data. It is also noteworthy that the range-calibration methods that have been used are neither simple nor precise.

7.4 RADAR MAINTENANCE

7.4.1 Introduction

The problem of radar maintenance for an airborne radar bombing system, namely, attaining and maintaining peak radar performance, is the same as for an *aircraft to surface vessel* [ASV] radar system (Section 5.1). The addition of such features as range units, computers, special antennas, and provisions for beacon bombing, to convert radar search systems to radar bombing systems, imposes further requirements on the parameters which have to be measured for complete maintenance of a radar bombing system. Special items of test equipment and test points for connecting the new items of test equipment to the radar system are required. Instruction literature for maintenance must be appropriately annotated, and the maintenance training program must be suitably expanded. Also, the type of installation of radar bombing systems in various aircraft imposes specific requirements on the design of such systems to insure complete accessibility of the test panel and other external test points, with particular reference to those essential for checking the range unit, computer, and antenna alignment.

7.4.2 Special Test Equipment

RANGE UNIT TEST SET

Most radar bombing systems have range units for providing accurate range marks and for furnishing requisite information for the bombing computer. It is desirable to know whether the range units are working properly, both as separate major assemblies and also when connected to the radar system proper. Also, it is desirable to know and to be able to check the calibration of the range units, unless they are self-calibrating. The particular checks and calibrations to be made will depend upon the design of the range unit used. However, general types of checks and the reasons for making them will be indicated in the following paragraph.

As indicated in Section 7.3.3, the range units associated with radar bombing systems provide the timing or synchronization for the entire radar system. Thus, the trigger for the modulator and for the indicator sweeps is provided by the range unit. In the range unit described in Section 7.3.2, the latter trigger may occur at any time within 6 miles (75 μsec) before and 6 miles after the modulator trigger. The range unit itself is crystal-controlled and provides accurate 1-, 5-, and 10-mile range marks, and a variable range mark which can be varied from ½ to 15 miles in range (for measuring the range of the altitude signal and the slant range of the target), or which is delayable in steps of 10 miles. It is necessary to ascertain if there is jitter in the 1-mile pip generator, the 10-mile pips, the modulator trigger, or in the phantastron delay, if this is used, since jitter of this kind is reflected in range errors. Furthermore, since the selector gate selects each 10-mile mark, it is important to know that the center of the gate is at the center of the selected 10-mile mark; otherwise an error in range is introduced.

Two general types of test calibrators, both crystal-controlled, have been designed for calibrating range units of this type. One provides accurately spaced positive or negative marker pulses which can be adjusted in phase from zero through 360 degrees with respect to the trigger which it provides. The range marks have a spacing of 500 yards and an accuracy of spacing of 0.1 per cent, with a jitter with respect to the synchronization pulse of 0.02 μsec. The trigger output pulses are positive or negative, up to 50 volts amplitude, of 0.8-μsec duration, and have a recurrence frequency of 400, 800, 1,600, or 2,000 pulses per sec. This type of test calibrator was used with such equipments as the AN/APA-5 and the AN/APQ-7.

The other type of calibrator incorporates an 80.86-kc crystal-controlled circular sweep (type J) and three linear sweeps (type A) of 1, 30, and 350 nautical miles. These are precision sweeps. The circular sweep can be synchronized with an 80.86-kc sine wave, and the linear sweeps can be obtained if the unit is triggered externally (from other than a sine wave oscillator), although in this latter case the sweeps are not precision sweeps. The sweeps can be delayed from 0.8 to 50 nautical miles with an error of less than 1 per cent in linearity; 10-mile points are marked on the dial on the face of the cathode-ray tube indicator which is included in the unit. A video amplifier, which has a 3-mc bandwidth and a fixed gain of 12, is also included. A positive or negative trigger output is provided at pulse recurrence frequencies between 160 and 2,000 c. Correspondingly, the test calibrator can be synchronized by positive or negative triggers as indicated above, at pulse recurrence frequencies up to 400 c. Units of this kind were used with systems such as the AN/APS-15 series and the AN/APA-30.

COMPUTER TEST SET

The computer is as much an integral part of a radar bombing system as the range unit (see Chapter 8). The maintenance requirement for a computer depends entirely upon the nature of the computer and its connection to the range unit. Thus, for a manually operated computer, such as used in the AN/APS-15, the bombing problem is solved by manually feeding to the computer information obtained from the range unit (such as altitude and slant range), the airspeed, the drift angle, and information obtained from tables for the type of bomb used. A computer of this kind requires no special maintenance other than that required for normal satisfactory mechanical operation; nor does the bombing position computer for Shoran (see Chapter 10). The Shoran computer is more complicated than the manually operated computer mentioned above but is designed so that calibration of the range component of trail, the limits of cross trail, the limits of range component of trail, and the speed check (measuring the time required for the computer to run out to 4 miles, on the speed counter) can be carried out without special test equipment.[85] In this case, it is necessary only to detail the calibration and checking procedure. Other computers, such as the one designed for the GPI (see Chapter 9), are self-calibrating also.

One type of computer test set has been designed to check the ability of a radar system to track smoothly and accurately. This test set also checks the horizontal range mechanisms and measures with great accuracy the voltages developed in various portions of the computer. A vacuum tube nullmeter compares a known adjustable voltage with the voltage being measured, and reads zero when they are equal. Range is indicated in terms of voltage ratios which are then multiplied by the proper scale factor for the equipment under test to obtain the actual distances. The accuracy of the potentiometer setting is one part in 2,500, and that of the feed setting is one part in 1,000. Manual or motor operation is provided.

Another type of computer test set, such as is used in toss bombing (see Chapter 12), provides a doppler simulation to give the range rate and provides a delay equivalent to the slant range. Altitude calibrations can also be made.

ANTENNA ALIGNMENT

For certain systems, such as the AN/APQ-7, it is necessary to check the antenna for accurate alignment with the radar system. Various methods of achieving this alignment have been effected using a signal generator test set and a portable synchroscope (which can be used conveniently at the aircraft). The procedure is greatly facilitated by use of a suitable test indicator, which is a selsyn unit with a calibrated dial to permit manual rotation of the selsyn rotor through a prescribed number of degrees.

SHORAN TEST EQUIPMENT

The maintenance of the Shoran system is somewhat different from that of a microwave radar bombing system, although the concepts of maintenance philosophy, design considerations, instruction literature, and training still obtain. The Shoran test equipment consists primarily of a frequency meter accurate to within 0.2 per cent; a heterodyne frequency meter, accurate to within 0.05 per cent; a power meter, good to within 15 per cent; a signal generator (similar to the General Radio type 804), and an oscilloscope-synchroscope.

BEACON TEST EQUIPMENT

Beacon test equipment is generally of three types, namely: that which provides a quick, overall check at the aircraft, for use with lightweight aircraft beacons; that which provides a more complete check, such as on the bench but which is still quasi-portable; and that which is built into the beacon system as part of a permanent installation.

A test set for performing quick, overall checks at the aircraft need only provide a pulsed r-f signal whose power output, which is monitored, is adjustable so as to barely trigger the beacon; a means of measuring the beacon's output power; and a cathode-ray tube on which the beacon code can be viewed. The actual requirements of such a test set are determined by the type of beacon under test. Thus, a test set for a quick check at the aircraft might have to provide paired r-f pulses of several fixed separations (which can be selected by a switch, for example) of two levels: one directly from the output of the oscillator (for purposes of calibration such as with a power meter); the other, at a different level (−20 db for example), for providing a signal which will enable the rejection of receivers whose sensitivity is below a prescribed amount. Also, a measurement of the frequency of the input and the output to within 0.5 mc might be required, as well as a means of measuring the beacon power output and beacon code.

Test equipment for making more complete tests on beacons includes the following: (1) a signal generator test set — capable of measuring beacon power ouput, beacon receiver sensitivity, overall bandwidth, and frequency — which provides fixed output pulses of 1 or 2 μsec duration and a pulse variable in duration from 0.2 to 5.5 μsec that is delayable from 10 to 200 μsec; (2) an oscilloscope on which the r-f pulse durations can be measured accurately, using an r-f envelope viewer; (3) an r-f dummy load; (4) a voltage divider; (5) a pressurization pump; (6) a means of making standing wave ratio measurements and, possibly, (7) a spectrum analyzer. The signal generator test set and the oscilloscope are part of the permanent installation.

Thus, for checking a beacon, it is generally desirable to check the minimum r-f signal on which the beacon will trigger, the pulse durations to which the beacon responds, beacon receiver sensitivity, and the beacon code on an oscilloscope capable of displaying the pulse durations accurately.

GPI Test Equipment

The *ground position indicator* system [GPI] (Chapter 9) was designed so that no special items of test equipment would be required. The general items of test equipment include a test calibrator for the range unit, such as one with a circular precision sweep, a portable oscilloscope-synchroscope for use at the aircraft and one providing more accurate displays for use at the bench, a bellows for applying constant pressure to the airspeed meter to check the integrators, a means of compass alignment, a stop watch, and the other items of test equipment, such as the signal generator test set.

Conclusion

The above brief discussion of test equipment serves only to illustrate the additional maintenance problems that result in changing from a search to a bombing radar. The fundamental radar maintenance problems described in Section 5.1 still exist for bombing systems and must be considered in the design of any radar set.

Chapter 8

BOMBING COMPUTERS FOR RADAR MAPPING SYSTEMS

8.1 THE COMPUTER PROBLEM

8.1.1 Introduction

In Chapter 7, a radar mapping system was defined as a radar equipment which presents on a scope a map of the terrain below and around the aircraft in which it is installed. Similarly, a bombing computer for a radar mapping system is defined as a computer which determines the time, place, and heading at which to release bombs in order that a target designated on the radar scope will be hit. The designating index usually consists of the intersection of a range mark and an azimuth mark which is made to coincide with the target signal on the radar scope. Several such bombing computers are analyzed in the present chapter.

Three general classes of computers are considered: nonsynchronous computers, semi-synchronous computers, and synchronous computers. In this classification, synchronous computers are defined as those computers which, by nature of their design, obtain data pertinent to release by a technique of continuous synchronization of a computer index with the target. These are contrasted with nonsynchronous computers which determine the release point, designate this on the *plan position indicator* [PPI] by a computer index, and require steering of the aircraft until the index and target coincide. The semi-synchronous computers make a partial synchronous and partial impact prediction solution by attempting to establish a computer index rate which keeps the index in synchronism with the target. The computer index, as discussed here, would be the cross hairs of the sighting telescope for a visual bombsight, or for a radar, the intersection of an azimuth mark and a range mark on a radar scope.

The synchronous computer types are particularly satisfactory for radar since they permit maximum use of information about the target before the target is at such close range to the aircraft as to become badly distorted and confused. Most of the computers discussed herein fall into the synchronous or semi-synchronous classification. However, the first radar computer designed for over-land bombing use was of the nonsynchronous, impact-prediction type. The production versions of this computer were incorporated in the AN/APS-15 and AN/APQ-13 radar equipments. Another type of impact-prediction computer was used with the AN/APQ-7 (Eagle) equipment. These computers are discussed in Section 8.2.1.

The next step taken to improve radar bombing was to supply radar range and angle information to the Norden visual bombsight in an attempt to reap the benefits of a Norden synchronous computer. Since this method also pointed the visual telescope at the target by means of the radar, any break in clouds or in the smoke covering the target could be used for visual bombing. Furthermore, since the Norden sight was synchronized with the target by the procedure, its bomb-release mechanism was used instead of depending upon the information from the radar picture which became badly distorted as the aircraft approached the bomb release point. This semi-synchronous technique was developed as an interim measure pending the advent of fully synchronous schemes. Other interim computers were the Visar and Nosmo which are completely synchronous in range but not in azimuth.

The list of completely synchronous computers includes the AN/APQ-5, the AN/APA-5, the MX-344, the *ground position indicator* [GPI], the AN/APQ-10, and the *universal bombsight* [UBS] computers.[81a] In this chapter the AN/APQ-5, AN/APA-5, and MX-344 computers are described and GPI is discussed in Chapter 9. This means that with one exception, only the synchronous computers that were developed at the Radiation Laboratory will be discussed in this book. The single exception is the MX-344 computer which was designed at Bell Telephone Laboratories. (The AN/APQ-10 and UBS were also developed at Bell Telephone Laboratories.) Of the computers discussed in the following sections only GPI attempts to solve all four problems in bombing, namely, navigation to the target area, identification of the target, computation of the release point, and steering to the release point. The others calculate the release point and steer to the release point but depend on radar pilotage or other means for navigation, and visual (optical or radar) recognition for identification.

The impact-predicting and semi-synchronous systems are all limited to straight-line, nonjinking bomb runs with the additional possibility of range-only offset. (In offset bombing, a bomb run is made by using a radar or optical reference point which is located at a known distance and direction from the target to determine the release point for the target). Of those classed as synchronous computers, the AN/APQ-5, AN/APA-5, and MX-344 are limited to straight-line nonjinking bomb runs. The MX-344 is also capable of offset bombing unlimited in azimuth but limited in range to approximately 10 miles. However, the accuracy falls off when azimuth angles greater than 60 degrees from the line between target and reference point are used. By the use of an attachment, it is also possible to use the AN/APA-5 for offset bombing limited in range to 5 miles and in azimuth to 45 degrees from the target to reference line. GPI provides an offset solution (unrestricted in azimuth) out to ranges of approximately 10 miles from the target in any direction.

8.2 NONSYNCHRONOUS COMPUTERS

8.2.1 Impact-Predicting Computers

The first radar blind bombing equipments consisted of modified search radar sets to which had been added a precision range unit and a simple bombing computer. The target was identified on the PPI and the aircraft was steered toward the target by observing it on the PPI. The bombing computer and range unit were used to create a *bomb release circle* on the PPI. This circle indicated the slant range from the target at which the bomb was to be released in order to score a hit. Accordingly, the bombs were released manually when the target reached the bomb release circle. These computers did not provide any means for determining drift or ground speed. Those important factors must be determined by other means.[52d] Although this type of radar bombing has exhibited relatively low accuracy, it played an important role in the war against Germany and is described here principally because of its role in the development of radar bombing. The original bombing radar set was the British H2S equipment operating with 10-cm radiation. The principles of that equipment were embodied in the American 3-cm H2X radar equipments. The Eagle (AN/APQ-7) equipment adapted those principles to a high-resolution radar system. Several typical impact-predicting bombing computers will be discussed in this section.

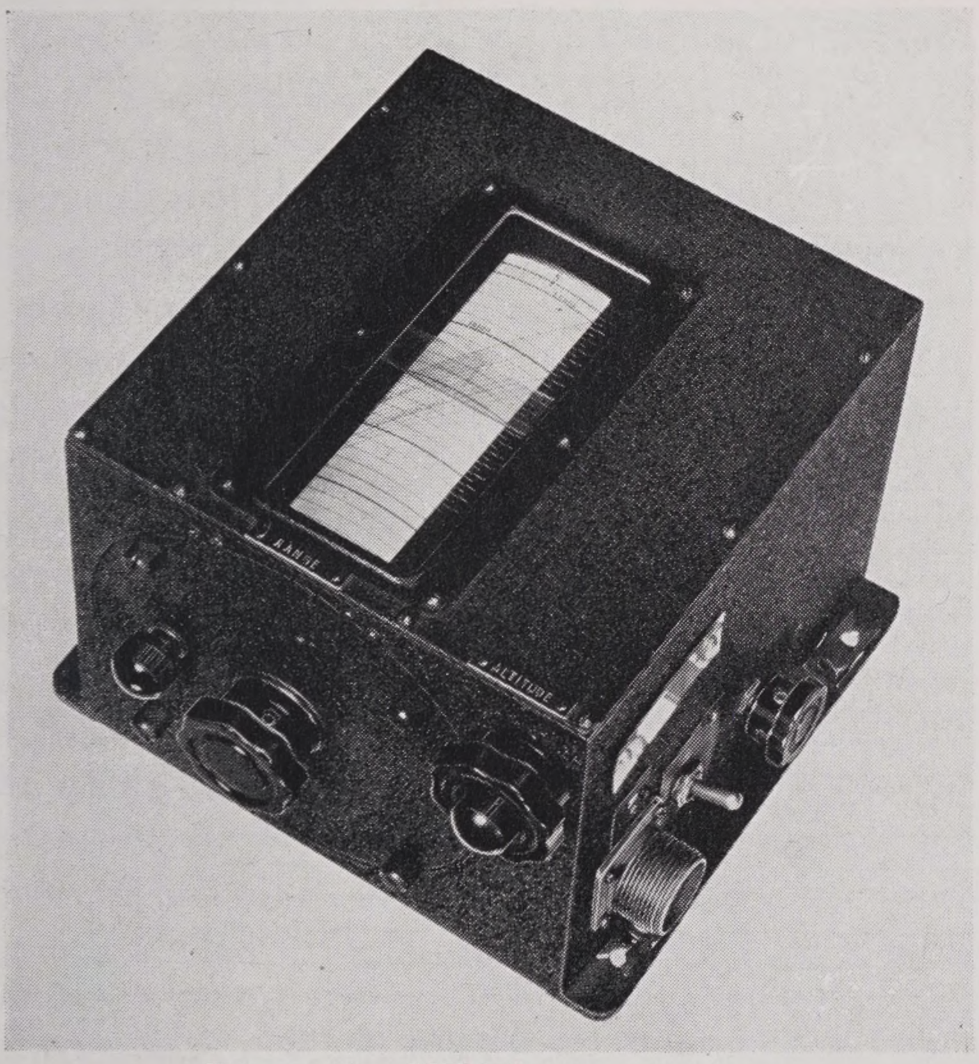


FIGURE 1. H2X drum computer.

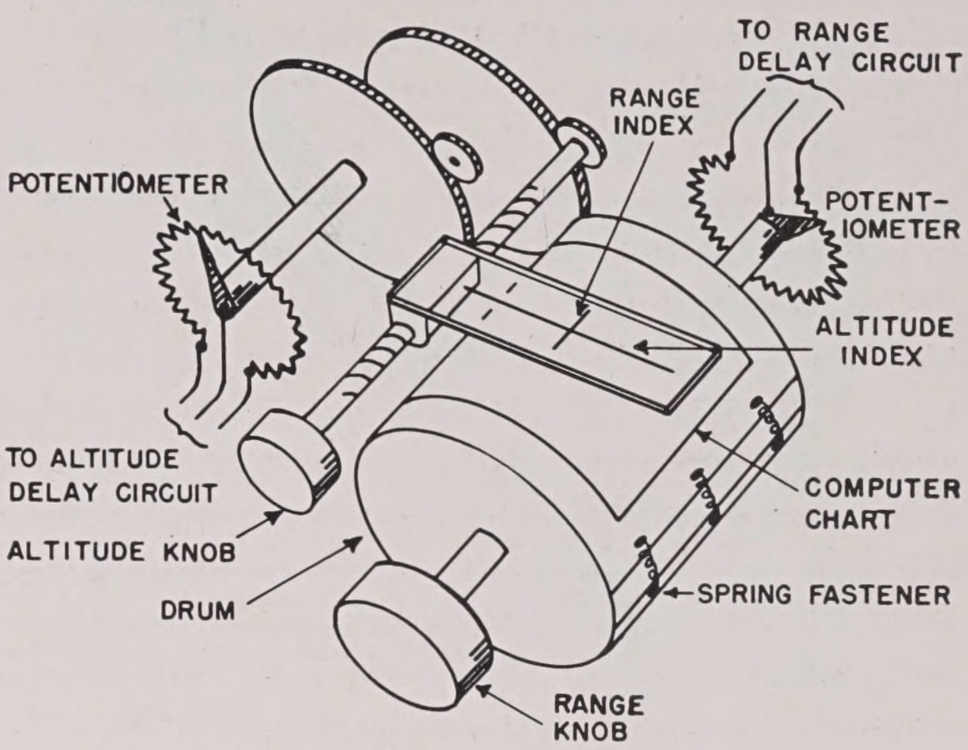
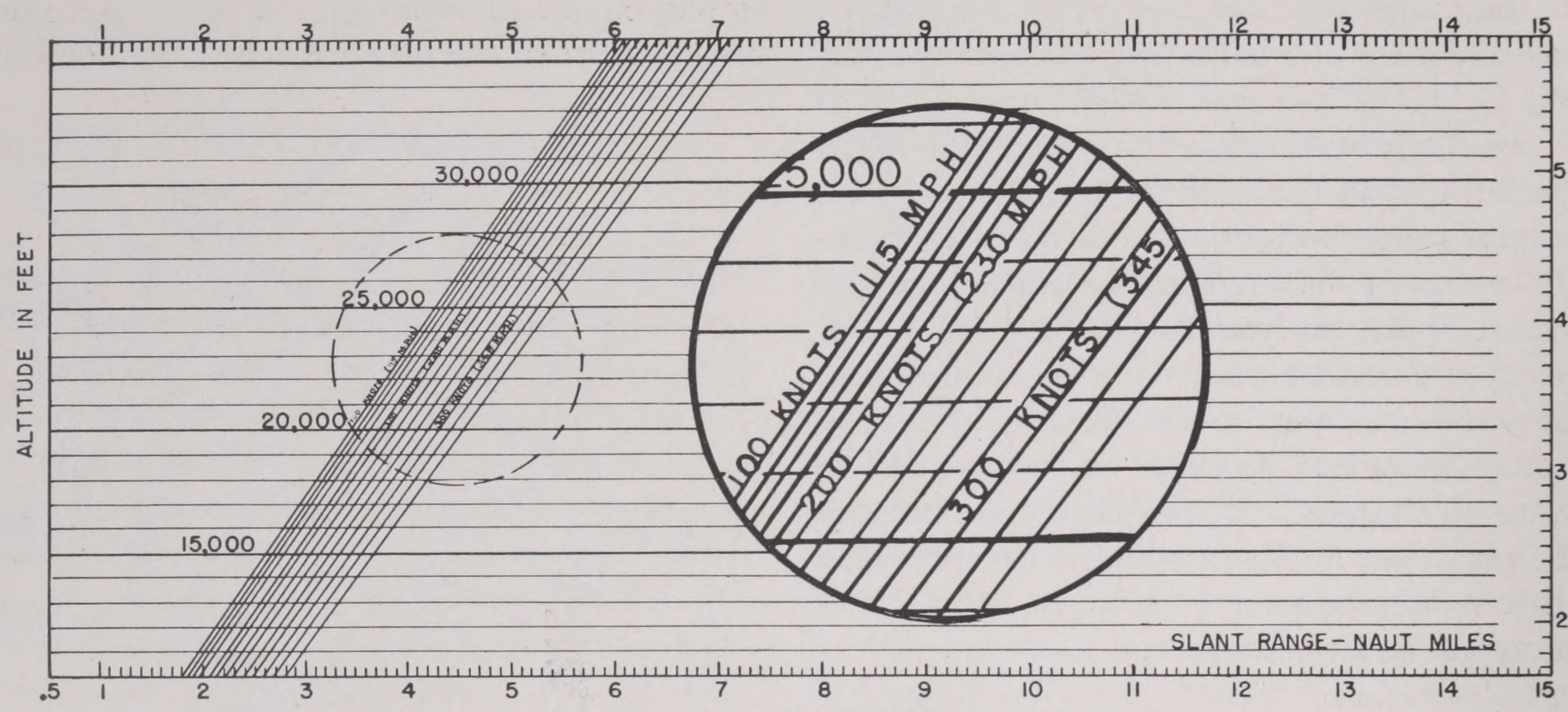


FIGURE 2. Diagram of H2X drum computer.

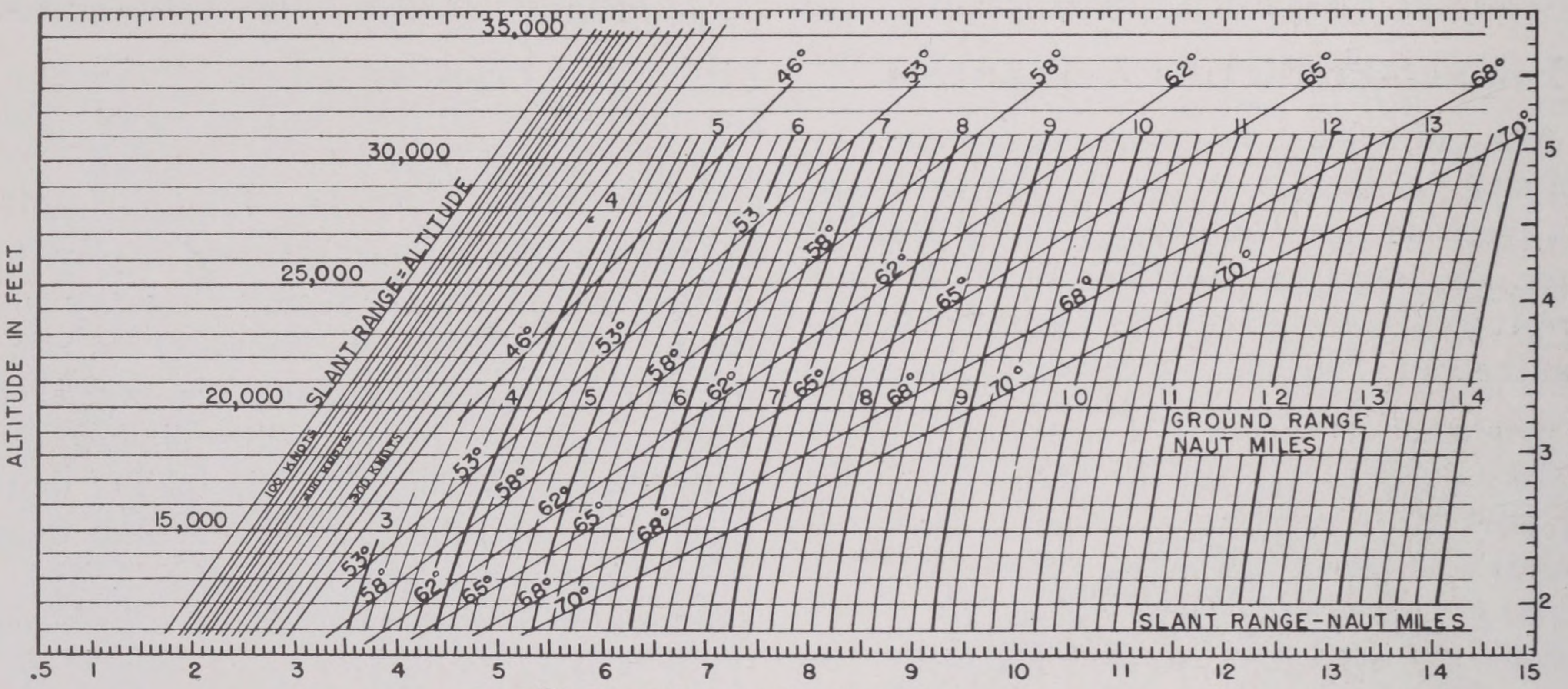
H2X DRUM COMPUTER

The term H2X includes two particular radar systems that were produced in large quantities. These are the AN/APS-15, which was widely used by the 8th and 15th Army Air Forces for the bombardment of German-held territory during 1944 and 1945, and the AN/APQ-13, which was extensively used by the 20th Army Air Force against the Japanese in the Pacific Area during those same years. The original bombing computers for both systems were identical and the circuits of their range units were similar. The AN/APS-15 was used in this original form by the 8th AAF in England during the first part of 1944 but the AN/APQ-13 was not widely used until the $h + b$ computer chart, described later, was incorporated.

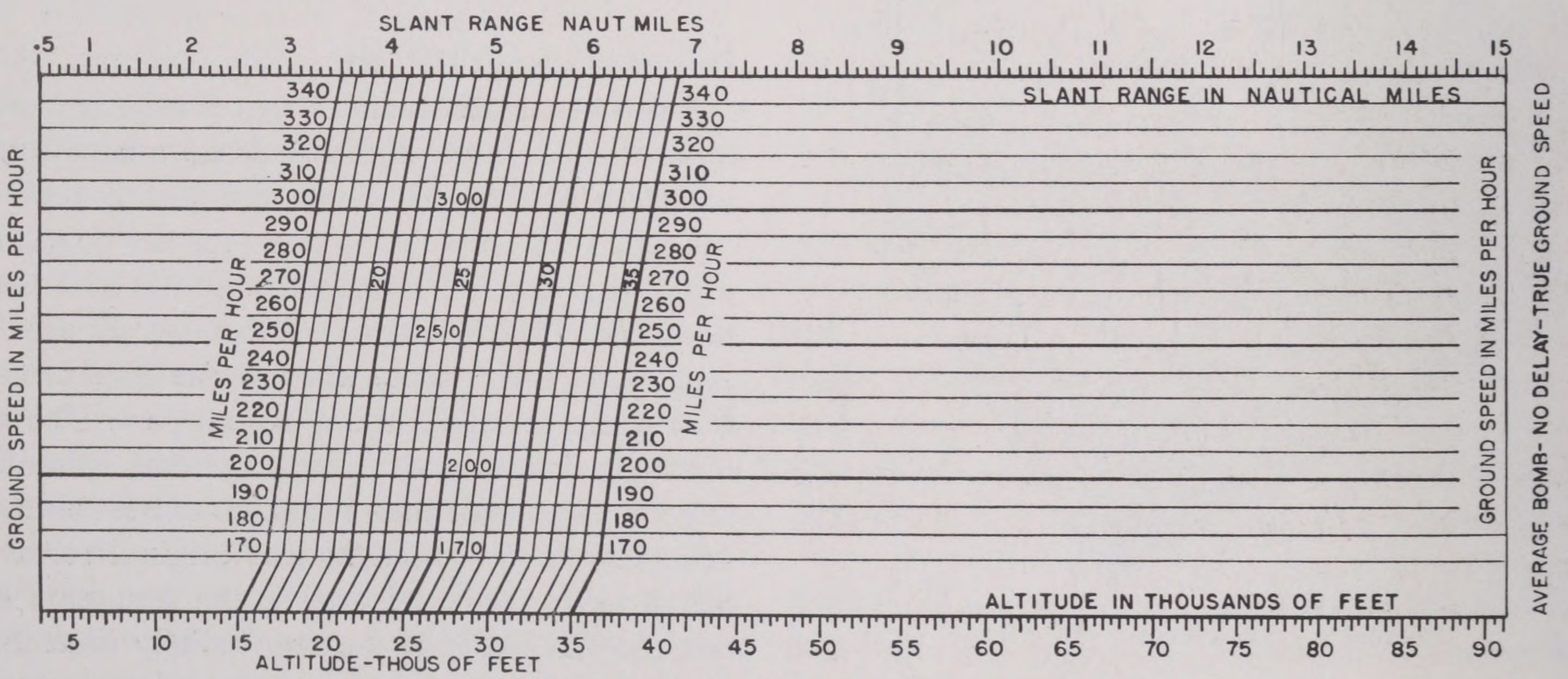
The H2X drum computer is illustrated in Figures



A ORIGINAL H2X DRUM COMPUTER CHART



B 8TH AAF CHART FOR AN/APS-15



C MODIFIED CHART FOR AN/APQ-13

FIGURE 3A, B, C. Charts used on H2X drum computer.

1 and 2. The range knob rotates a cylinder or drum behind a fixed range index (parallel to the axis of the cylinder). The range knob also turns a potentiometer which provides control voltage for a variable range delay circuit in the range unit. The altitude knob on the drum computer moves an altitude index in front of the cylinder in a direction parallel to the axis of the cylinder. A potentiometer is also turned by the altitude knob, and this provides control voltage for a variable altitude delay circuit in the range unit. Both delay circuits begin timing when a transmitted pulse is started. At the end of the variable altitude delay, the PPI sweep is started. Twelve μsec later (to allow for the slow starting PPI sweep), an altitude marker is produced on the A scope. Because of a minimum altitude delay, the altitude marker cannot be set to less than about 10,000 ft. At the end of the variable range delay, a bomb release marker is displayed. The bomb release marker appears on the PPI as a concentric circle.

A chart is wrapped around the drum to provide computing scales. Several different charts used with this computer are shown in Figure 3. Moving horizontally (parallel to the longer edges) on any one of these charts is the equivalent of turning the range knob, and moving vertically (parallel to the shorter edges) is equivalent to turning the altitude knob.

Only two operations are required to set up the proper bomb release circle on the PPI. First, the altitude knob is rotated until the altitude marker just touches the first ground return on the A scope. When this is done, the altitude cursor will indicate on the vertical scale of the computer chart, Figure 3A or B, the absolute altitude at which the airplane is flying. Alternatively, if the absolute altitude is known by other means such as a barometric or a radio altimeter, the altitude cursor may be set to that value directly. This first operation automatically sets in the proper amount of sweep delay to close the altitude circle on the PPI. The second operation consists of turning the range knob until the intersection of the range and altitude cursors falls over the proper ground speed line. This positions the bomb release circle on the PPI. The correct ground speed should be determined from navigational data collected enroute.

Because the resolution of the radar presentation is much poorer than that afforded by the optics of a visual bombsight, the overall bombing accuracy to be expected by the impact-predicting radar bombsight is accordingly poorer. For this reason, several simplifying assumptions were made in the design of the chart for the drum computer, thus allowing the operator more time to devote to the difficult problem of target identification. The variation of trail with bomb type was neglected and calculations for trail and time-of-fall based on the ballistics of the AN/M-43 500-lb general purpose bomb were incorporated in the chart. This was the bomb most widely used for strategic bombing in Europe. The ballistics of the heavier bombs did not differ too much from these and correction factors were later supplied for use with the AN/M-38A2 100-lb practice bombs used for training. The assumption that airspeed was equal to ground speed introduced a small error in trail and completely ignored the effect of cross trail. Field experience has shown the wisdom of these assumptions since errors introduced by them are small in comparison with the actual combat bombing errors.

The discussion of range measurement in Section 7.2.1 indicates that several sources may contribute to errors in radar range measurements. These errors, if sufficiently large, will be reflected in the overall bombing accuracy of the equipment. This was believed to be true in the use of H2X equipments, and a modification was made to the computing method just described. The modification serves to reduce the effect of some of the errors and is explained in the discussion of the $h + b$ technique below.

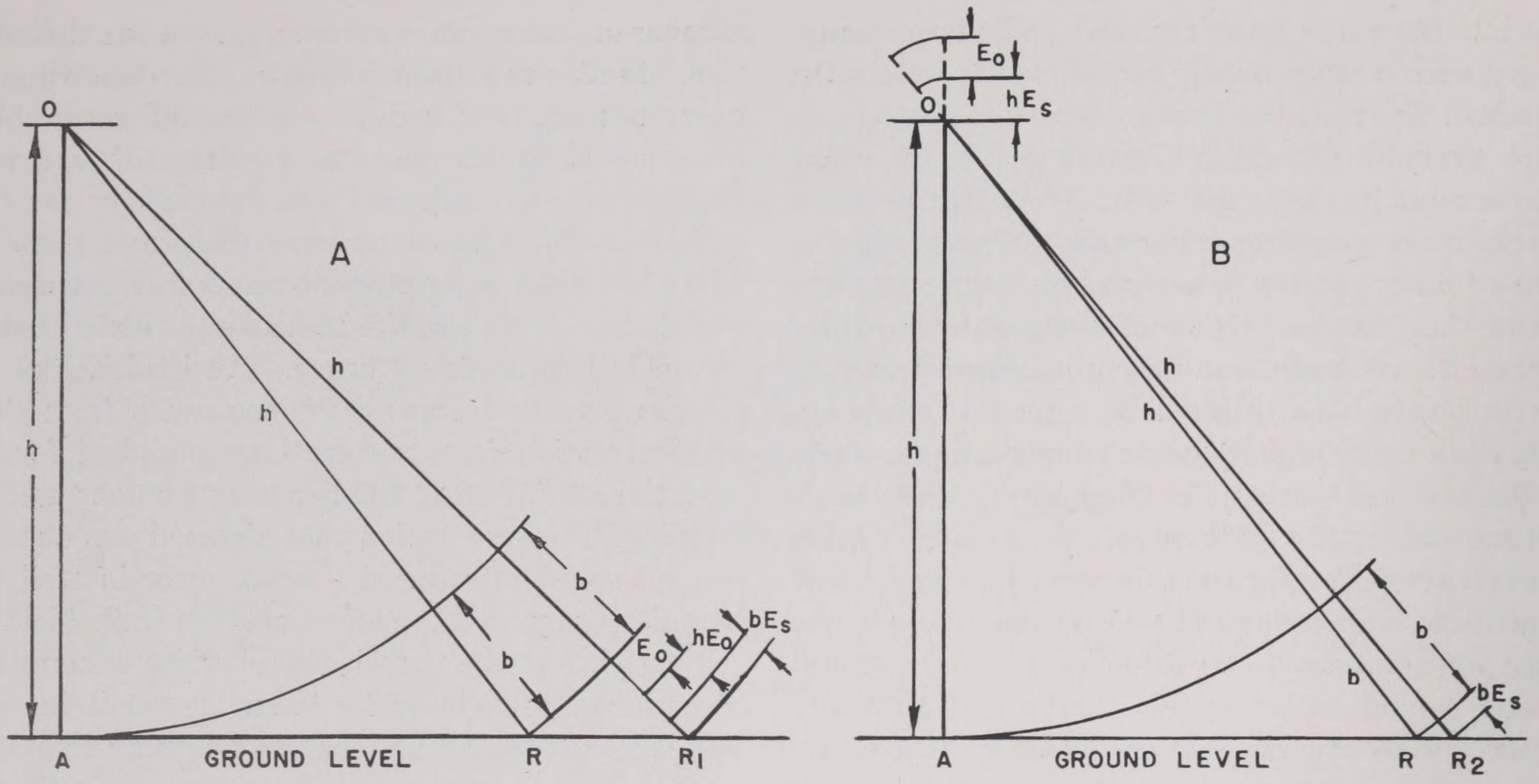
$h + b$ TECHNIQUE

One of the problems encountered in the use of the H2X equipments was that of maintaining proper calibration of the altitude and range delay circuits. Not only was the process of calibrating these circuits time-consuming, but also their constants were observed to change when they were flown to high altitudes. The error (ΔR) in measuring a slant range R is

$$\Delta R = E_0 + RE_s \tag{1}$$

where E_0 is the zero error and E_s is the slope error. This is true for both the altitude delay circuit and the range delay circuit, both of which contributed to the bombing error.

The $h + b$ technique is one in which the bomb release range is considered as a slant range, $\overline{OR}$, equal to the sum of the altitude, h, and an additional distance, b, as shown in Figure 4. This shows how the $h + b$ technique reduces any bombing error caused by an inaccurate calibration of delay circuits. The distance b varies with bomb type, altitude, airspeed,



ORIGINAL H_2X COMPUTER

h + b COMPUTER

h = OA = true altitude
OR = true slant range to target
b = OR − h
RR_1 = bombing error with original H_2X computer
RR_2 = bombing error with h + b computer

E_0 = zero error of range circuit
E_s = slope error of range circuit (fraction of true range)
hE_s = slope error for range h
bE_s = slope error for range b

Note. In Figure 4A, hE_0 should be hE_s.

FIGURE 4A, B. Reduction of bombing error by use of $h + b$ technique.

and wind. Both h and b are measured by the same delay circuit. Referring to Figure 4A, $\overline{RR_1}$ is the bombing error which would occur with a computer of the original H2X type as a result of assumed values of zero and slope errors in the range delay circuits. The bombing error shown in that figure is based upon the assumption that the true altitude was set into the computer. If the altitude used was obtained from the radar, zero and slope errors in the altitude delay circuit would cause an additional bombing error which might be either additive or compensative. In Figure 4B, $\overline{RR_2}$ represents the smaller bombing error which would result from the same zero and slope errors if the $h + b$ principle is applied to the H2X computer. Note that $\overline{RR_2}$ is considerably shorter than $\overline{RR_1}$. A second order error would be introduced by the use of an incorrect value of h in determining the value of b but this has only a negligible effect.

Modified H2X Drum Computers

The AN/APS-15 drum computer was modified to incorporate the $h + b$ principle described above by adding a slant-range = altitude (or $b = 0$) line to the computer chart. This line, as shown in Figure 3B, is just to the left of, and almost parallel to, the system of ground speed lines. Using such a chart, the procedure for setting up the bomb release circle is as follows. With the altitude cursor set near the bottom of the scale and with a fast sweep (short range) on the PPI to create a large diameter altitude circle, the range knob is turned until the bomb release circle just touches the altitude circle. This evaluates the altitude, h. This altitude is transferred to the altitude scale of the computer chart by turning the altitude knob until the intersection of the range and altitude cursors lies over a point on the slant range = altitude line. Turning the range knob to place the intersection of the range and altitude cursors over the proper ground speed line on the computer chart completes the operation required to set up the bomb release circle.

With the modification described above, it is desirable to have the altitude delay circuit adjusted with a small negative error in the zero setting in order to create PPI presentation with a small diameter altitude circle when the procedure of setting up the bomb release circle is completed. It is usually preferable, however, to completely divorce the altitude knob from the potentiometer controlling the PPI sweep delay circuit. The potentiometer may then be used independently to adjust the PPI sweep delay. A computer of this type was designed for use with the AN/APS-15.

The original AN/APQ-13 drum computer chart was replaced by the one illustrated in Figure 3C in order to make use of the $h + b$ technique in a slightly different manner from that described above. This was done before the AN/APQ-13 was put into large-scale use. The use of the intersection of the range and altitude cursors as an index was made completely independent of the altitude delay circuit. The horizontal scale at the bottom of the computer chart is an altitude scale calibrated in thousands of feet. The vertical scale is a ground speed scale calibrated in miles per hour. Diagonal lines extend the altitude scale across the ground speed scale for those altitudes between 15,000 ft and 35,000 ft. To use this chart the altitude h is measured on the altitude scale on the bottom of the chart by matching the bomb release circle to the altitude circle on the PPI. Setting the range index over the intersection of the diagonal altitude line and the proper ground speed line adds the necessary range increment b to produce on the PPI a bomb release circle of a diameter corresponding to the slant range, $h + b$, at which bombs should be released.

Dial Computer

The AN/APS-15A Dial Computer was designed to overcome, wherever possible, the complaints that arose out of the early use of the original H2X drum computer. The principal objectives in this design were the incorporation of the $h + b$ technique to reduce the effect of range circuit errors, and the provision of convenient scales which would enable the operator to make more precise settings.

A photograph of the dial computer is shown in Figure 5. The altitude knob, which drives the arm of the potentiometer controlling the range delay circuit, (note this is the range rather than the altitude delay circuit) can be turned only if the ground speed knob is set at the zero position. The altitude scale indicates slant range up to 90,000 ft, in 100 ft intervals. The ground speed knob rotates the body of the same potentiometer, thus adding an increment of range to that set in by the altitude knob. Twelve ground speed scales which cover the possible combinations of three groups of bomb types and four ranges of indicated airspeed, can be inserted. The type of airplane in which the equipment is installed determines the indicated airspeed range, and thus reduces to three the number of scales required for any particular installation. Bomb types were divided into three groups: light, medium, and heavy; and ground speed scales were based on the ballistics of the AN/M-38-A2 (100-lb) practice bomb; the AN/M-43 (500-lb) general purpose bomb; and the AN/M-34 (2,000-lb) bomb. In general, the use of a different ground speed scale for each group of bomb types was not justified in terms of the accuracy of aiming possible with the AN/APS-15 PPI presentation, but it was believed that the availability of such scales might have a favorable psychological effect on the operators. No addition to the operator's duties during flight would result because the proper scale could be placed in the computer when the bombs were loaded into the airplane. A third knob (sweep timing) controls the starting time of the PPI sweep over a range corresponding to 6 miles before the transmitted pulse to 6 miles after the transmitted pulse.

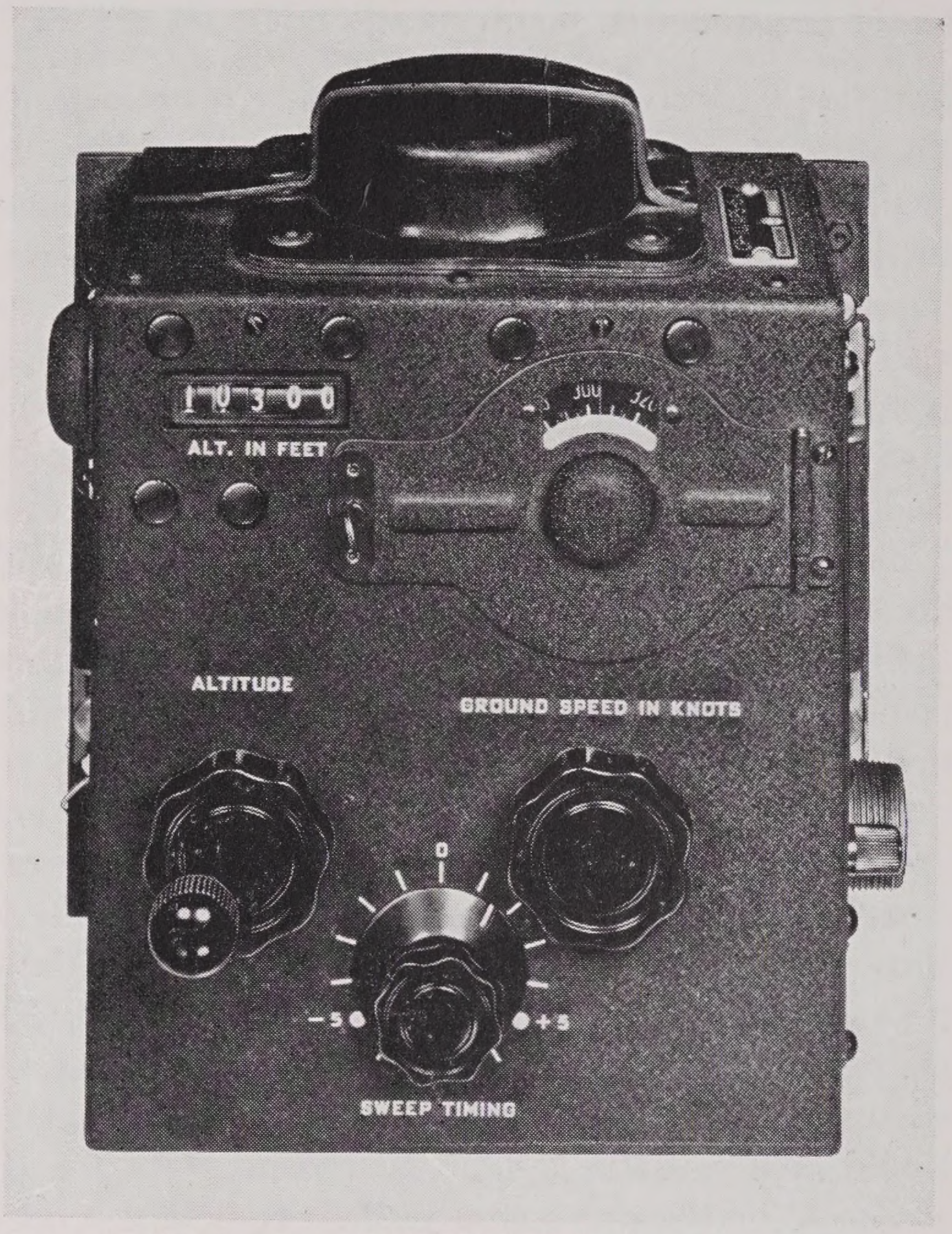


Figure 5. AN/APS–15A dial computer.

The operating procedure to set up the proper bomb release circle with the AN/APS-15A dial computer consists of two steps. With the ground speed knob at zero the altitude is determined by matching the bomb release circle with the altitude circle on the

PPI. (The altitude scale now indicates the height of the airplane above the terrain.) The ground speed, which was determined from navigational data, is then set into the ground speed knob, thus adding the range increment *b* to the altitude *h* which correctly positions the bomb release circle on the PPI.

Factors Contributing to Inadequacy of Impact-Predicting Computers

The poor results usually obtained with the impact-predicting computers are caused by certain fundamental deficiencies of the H2X radar equipments as well as by tactical considerations. An example of the latter was the division of responsibility between the optical bombardier and the radar operator which occasionally led to confusion during the bombing run. This confusion was intensified by the fact that final decision as to whether optical bombing or radar bombing would be most effective in many cases could be made only after the bombing run was well under way.

No accurate direct method of measuring ground speed or drift is provided. Although good navigational procedure includes frequent calculation of those quantities, the tension and excitement of battle just before and during the bombing run often causes errors in such calculations. An automatic means of determining and setting in those factors would be a valuable asset.

The second major technical deficiency which contributed to the inadequacy of impact-predicting bombing computers was the distortion of the PPI presentation at ranges near the bomb release range. This distortion made the determination of the time at which the target crossed the bomb release circle extremely difficult. Several factors described below contribute to that deficiency:

1. The ratio of ground range to slant range changes very rapidly with range at short ranges and therefore causes severe distortion near the center of the PPI. This range distortion, discussed in Section 7.2.1, is particularly great at the high altitudes from which bombing is usually done.

2. The H2X antenna was deficient in two ways. The uneven vertical radiation pattern caused the sensitivity of the radar system to fluctuate with range in such a manner as to create concentric rings of bright and dim response on the PPI. (See Figure 4A, Chapter 7.) This required the operator to make frequent adjustments of the receiver gain and antenna tilt angle toward the end of the bombing run. The second deficiency was the increase in the azimuth beamwidth of the antenna at large depression angles which impaired the azimuth resolution near bomb release range.

3. The radar returns from the target area change considerably with aspect, thus changing the appearance on the PPI of the target area. This change of appearance is particularly great near the bomb release range.

The importance of the above deficiencies of the H2X with an impact-predicting computer was realized soon after that equipment was introduced into combat use by the 8th and 15th Army Air Forces. An attempt to overcome some of them resulted in the coordinated bombing technique described in Section 8.3.1.

8.3 SEMI-SYNCHRONOUS COMPUTERS

8.3.1 Semi-Synchronous Tie-in of Radar to Optical Bombsight

As previously stated, the two major deficiencies of the radar bombing procedure using an impact-predicting computer are the deterioration of the radar presentation near the bomb release range and the division of responsibility between the radar operator and the optical bombardier who pursue independent bombing functions. The coordinated bombing procedure was developed to alleviate these deficiencies without waiting for redesign of the available radar and optical bombing equipment. This method was first used operationally and with marked success by the 8th AAF in bombing operations just prior to the invasion of the Normandy coast in June 1944.[77a] The 15th AAF also adopted this procedure at about the same time.

The Norden bombsight has an inherent accuracy many times better than that of the H2X equipment but is useful only when the target is unobscured by darkness, clouds, fog, or smoke. The H2X equipment, although much less precise, is not affected by cloud or smoke cover. As has been previously stated, it was desirable to bomb optically whenever possible and for that reason the decision between optical bombing and radar bombing was often deferred until the end of the bomb run, which resulted in much confusion. Moreover, the radar presentation is considerably better at ranges just a few times greater than the bomb release range than at the release range so that if bombing information could be obtained at the greater range, the accuracy of blind bombing would be improved.

The coordinated bombing procedure has been termed semi-synchronous because it involves point-to-point synchronization of the tracking mechanism of the Norden bombsight from radar data. The radar operator informs the Norden bombardier of the time when the radar presentation of the target on the PPI is at certain definite points which correspond to specific optical sighting angles. Although this is inferior to the method of direct connection between the H2X radar and the Norden bombsight afforded by the AN/APA-46 and AN/APA-47 (Nosmo and Visar) attachments (see Section 8.3.2), it required only a simple modification of the H2X drum computer chart and was therefore immediately available for combat use on a large scale.

The only essential equipment change was the addition to the drum computer chart of a series of lines converting seven selected sighting angles to slant range as a function of altitude. The sighting angles chosen were 70 (maximum for Norden bombsight), 68, 65, 62, 58, 53, and 46 degrees. These represent approximately equal intervals of ground range which, at 25,000 ft altitude, are about 1 mile in length. Actually, new computer charts were prepared which included these sighting angle lines and also a family of ground range lines, which were helpful for ground speed measurements, as well as a (slant range = altitude) line to make possible use of the $h + b$ technique described in Section 8.2.1. That chart is illustrated in Figure 3B.

The same coordinated bombing procedure was used for both visual and radar bombing runs and this avoided last minute confusion in borderline cases. Sighting angle data were transmitted from the radar operator to the bombardier, via the interphone. Although the procedure requires a high degree of coordination between those two persons, it was far superior to the earlier nonsynchronous bombing methods.

Before reaching the start of the bombing run, the bombardier sets into the bombsight all preset data such as disk speed, trail, approximate drift, and approximate ground speed, just as he would in a normal visual bombing run. He next sets the sighting angle index at 70 degrees and waits for the signal from the radar operator. The radar operator has set the range index of the H2X computer over the intersection of the 70-degree sighting-angle line and the proper altitude line. This creates a circle on the PPI which corresponds to the 70-degree sighting angle. At the coincidence of this circle and the target return, the radar operator signals the bombardier who immediately starts the Norden bombsight motor. If the preset data and the first check point were absolutely correct, the procedure could end here. Actually, this is not true, and the additional check points are used to correct the rate and displacement knobs of the Norden bombsight. This effectively causes the telescope of the bombsight to track the target and permits quick visual correction if an opening in the cloud or smoke cover appears. Whether a visual correction is possible or not, the tracking mechanism of the Norden bombsight automatically releases the bombs.

By the summer of 1944, when the AN/APQ-7 bombing radar equipment was nearing production, the coordinated bombing technique had proved its superiority over the impact-predicting method. Accordingly, a design change was made in that equipment in time to be used in combat by the 315th Wing of the 20th AAF. The modification took the form of a few circuit changes in the operator's indicator and the addition of two small boxes. One of these, the control unit, had controls for altitude adjustment (pulse matching on the A scope) and a switch permitting the use of either the original impact computer or the external components for synchronization. The arrangement also had the provision that either the box with selector switch for sighting-angle check points (using the same angles as with H2X) or the Nosmo attachment (see Section 8.3.2) when available, could be connected to the control unit. This arrangement was quite flexible in that three techniques were possible. In the rush of war, equipment design may be finished long before evaluation tests with prototype models are complete — thus this flexibility was highly desirable.

In the case of AN/APQ-7, the advantages of the Norden coordination are less clear. Because of the higher resolution and improved antenna coverage of AN/APQ-7, the target image is more sharply defined and can usually be tracked to the bomb release marker, thus eliminating the primary technical objection to the AN/APS-15 impact-predicting system that led to the development of radar-Norden coordination. In the case of AN/APQ-7 it would appear that when complete radar conditions are foreseen, i.e., 10/10 clouds or night, there might be some advantage in using the impact-predicting procedure and in avoiding the necessary high degree of coordination between radar operator and Norden bombardier.

8.3.2 Continuous Radar Tie-in with the Optical Bombsight

The check-point method of setting up the optical bombsight by using radar information, described in the previous section, provides only an approximate solution of the bombing problem. When the Norden bombsight is used as an optical bombsight under conditions of good visibility, the rate and displacement controls are continuously adjusted to keep the cross hairs on the target. In the check-point radar method, adjustments can only be made at a few (usually seven) fixed sighting angles since time does not permit a greater number of adjustments. It is clear that the bombing in the latter case will be less accurate than in the former, since errors in positioning the bombsight are obvious only at the specified sighting angles.[80a]

This deficiency of the check-point method was soon recognized and a number of methods of supplying more continuous radar information to the optical bombsight were conceived. By the end of World War II, production designs and systems had been completed for two of these methods, namely Nosmo (AN/APA-46) and Visar (AN/APA-47).[78a]

Design Principles of Nosmo, Visar, and Nosmeagle

Both Nosmo and Visar make use of the optical bombing computer mechanism (the rate end) of the Norden bombsight to solve for the correct bomb release point. The rate end (see Section 6.2.1) which normally drives the optical mirror of the bombsight, is coupled instead to a suitable nonlinear potentiometer. A voltage from the potentiometer is fed to the range circuits of the radar set where it controls the position of the bright ring of the PPI that is used as a bomb release index for the original impact-predicting method. In this case, however, instead of establishing one position on the PPI corresponding to the bomb release point, the operator adjusts the rate end to keep the bomb release mark continually touching the chosen target. In this way, radar sightings replace the optical sightings and the rate end operates in its usual manner to compute the bomb release point. It should be noted that the radar information is neither so continuous nor so accurate as optical sightings because of the lower resolution of the radar system and the slow rotation of the scanner.

Since the application of this type of bombing computer to any radar mapping system is obvious, it is not surprising that plans were made to adapt them to all three of the common bombing radar systems, AN/APS-15, AN/APQ-13, and AN/APQ-7. However, as a result of the abrupt termination of World War II, only a very limited amount of operational information on the performance of Nosmo or Visar is available. The testing carried out under the auspices of the AAF Board at Orlando, Florida, indicated that an improvement by a factor of about 2 was obtained in the bombing results, especially over complex targets. The AAF Board tests were terminated at the end of World War II, since both Nosmo and Visar were interim methods of providing synchronous bombing using readily available components, and they would be eclipsed by the development of better bombing computers such as GPI. In spite of their short life, these two computers served to emphasize the contributions that synchronous range tracking, pulse doppler ground track determination, and a synchronized optical bombsight could make in improving radar bombing.

Although both Nosmo and Visar employ the Norden rate end to solve the bombing problem, they differ markedly in other respects. Thus, when Nosmo is used, the radar operator adjusts an auxiliary Norden rate end to cause the bomb release circle to track the target on the PPI while the bombardier synchronizes the optical bombsight with the radar operator's rate end by watching an indicating meter. In this case, either rate end may be energized to drop the bombs. On the other hand, when Visar is used, the optical bombardier tracks the target on a remote PPI, located in the nose of the airplane, by using the same controls that adjust the optical telescope of the bombsight. Thus, in the Visar method, the principal function of the radar operator is to keep the radar system in good adjustment and to assist the bombardier in identifying the target correctly on the PPI screen. The resultant advantage of Visar is that both the bombardier and the radar operator adjust controls with which they are familiar. The main disadvantage of Visar is the necessity of training bombardiers in the often difficult task of interpreting the PPI radar picture. Visar also required that the bombardier be able to use either the radar PPI or the optical bombsight which is troublesome since light conditions are so different in the two cases.

The second major difference between Nosmo and Visar is the method of killing drift on the bombing run. When Visar is used, a reference azimuth line whose position is controlled by the drift knobs of the

Norden sight is displayed on the PPI. By an adjustment of these knobs, the airplane heading is changed through the automatic flight-control equipment or the pilot's direction indicator so that the ground track of the airplane passes through the target and the drift is killed. Nosmo, on the other hand, takes advantage whenever practicable of the innate ability of a radar system to determine the ground track of the airplane by an application of the pulse doppler phenomenon.[52, 8a] From a knowledge of the present ground track which may be rapidly determined by this means, corrections in heading are given to the pilot to bring the ground track through the target. Even when Visar is employed, the ground track, and hence the wind, may be determined by the Doppler method prior to the bombing run and used as an aid in presetting the Norden sight. It is noteworthy that, in both Nosmo and Visar, cross trail (Section 6.1.3) is neglected, which is usually permissible for common types of bombs.

With these exceptions, the technical design of both AN/APA-46 and AN/APA-47 is so similar that only the former will be described.

DESIGN OF NOSMO (AN/APA-46)

The design of the Nosmo radar bombing computer has been described in detail.[30] Only a brief description of some of the salient features will be undertaken here. As seen in the previous section, the Nosmo computer employs the Norden rate end to establish the correct release point and determines the correct bombing course by an application of the pulse doppler phenomenon.

The three most important components of AN/APA-46 are illustrated in Figure 6, namely, the computer, the control box, and the servo-amplifier. In addition, an antenna attachment, a junction box, a comparator meter for the optical bombardier, and an attachment to the optical bombsight, are required.

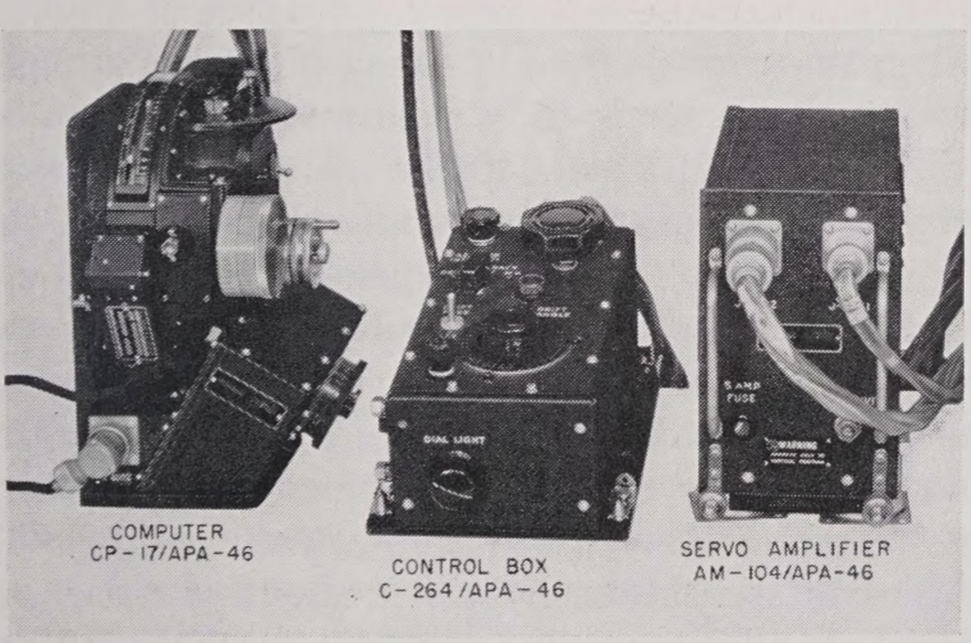


FIGURE 6. Major Nosmo components.

Pulse Doppler Course Determination. The first part of the bombing problem is determining the course that the airplane should fly. It is solved in the case of Nosmo by using the pulse doppler phenomenon. Nosmeagle, on the other hand, did not use this method of course determination. For a detailed description of the doppler phenomenon, see Part V and the R. L. Technical Series.[52] Briefly, whenever the radar scanner is pointed along the ground track of the airplane, the appearance of the radar echo returned from the ground area is characteristically modified. Therefore, by moving the antenna slowly through the region in which the suspected ground track lies, and examining the radar echo, it is possible to determine the ground track of the airplane within ± 0.5 degree over land. In rough air such as that over mountains the accuracy will be less, and it is not yet possible to make an accurate determination of ground track over water.[52]

In order to position the antenna slowly and accurately, a servomechanism is used so that the setting of a knob on the control box (see Figure 6) determines the direction in which the scanner is pointed. In addition to the positioning feature, the servomechanism also provides for the display of a radial mark on the PPI to indicate the ground track of the airplane on the radar map after the radar mapping feature is resumed. The radial mark may be made either bright or dark at the discretion of the radar operator and the use of the dark line will be preferable over built-up areas. Since the ground track will change whenever the airplane is turned and also whenever the wind shifts, a new determination of wind will be required periodically and as often as a turn is made. If the PPI presentation is stabilized, turns of 10 or 15 degrees can be made without a redetermination of ground track, since the drift angle does not change appreciably. The need for repeated evaluation of ground track is a disadvantage of the Nosmo technique because radar mapping must be suspended for 20 or 30 sec while the ground track is being resolved. This disadvantage could be eliminated by automatically displaying the instantaneous ground track on the PPI even though the antenna is continually scanning. The advantages to navigation and bombing of a radar display of the airplane's instantaneous ground track require no emphasis.

The doppler phenomenon might also provide an indication of the instantaneous ground speed.[52] Since ground speed is a major factor in establishing a bomb release point, future radar bombing computers will probably make greater use of the doppler phenomenon in measuring ground speed as well as ground track.

Rate Computation. The heart of the Nosmo scheme is the computer CP-17/APA-46, which consists of the Norden rate end (see Section 6.2.1), whose output shaft is coupled to movable arms of two potentiometers. One of these is a linear potentiometer of the same type that is attached to the rate end output shaft of the optical bombsight. The positions of the arms of both these linear potentiometers are controlled by the rotation of the output shafts of their respective rate ends. By impressing the same voltage across both potentiometers and making the difference in the voltage at the potentiometer arms zero when read on the bombardier's comparator meter, the optical bombsight can be synchronized with the Nosmo computer.

The second potentiometer, which is coupled to the Norden rate end of the Nosmo computer, is a nonlinear potentiometer. The voltage from the arm of the nonlinear potentiometer is connected to the radar range unit (see Section 7.2.1) and positions the bomb release circle on the PPI. When the correct calibration has been made, the bomb release circle indicates the slant range corresponding to the altitude of the airplane and the sighting angle indicated on the rate end. The method by which this is accomplished follows. The rotation of the shaft of the rate end, and consequently the motion of the arm of the nonlinear potentiometer, is proportional to the tangent of the sighting angle, that is, ground range divided by altitude. The nonlinear potentiometer is in series with a fixed resistor connected to ground potential. This resistor is so designed that the resistance from the arm of the potentiometer to ground potential is proportional to the secant of the sighting angle, i.e., slant range divided by altitude. If the sighting angle is zero (corresponding to a target directly below the aircraft) the arm of the potentiometer is at the end of the potentiometer connected to the fixed resistor. In this case, the voltage transmitted to the range unit corresponds to that of slant range equal to altitude. Therefore, by adjusting the voltage applied to the nonlinear potentiometer and fixed resistor network until the voltage across the fixed resistor brings the bomb release circle into coincidence with the altitude signal (see $h + b$ technique, Section 8.2.1), the Nosmo computer is calibrated for that particular altitude. Once this procedure has been carried out, the bomb release circle on the PPI will indicate the slant range which corresponds to the particular sighting angle indicated by the Norden rate end for the particular altitude at which the computer was calibrated.

When the computer has been adjusted in this manner, and the radar operator adjusts the rate end controls so that the bomb release circle stays in conjunction with the radar presentation of the target on the PPI, the correct sighting angle information is fed into the Norden rate end to permit it to calculate the bomb release point. In other words, Nosmo is one method of translating the slant-range information provided by the radar system into the sighting angle information for which the Norden bombsight was designed.

Although this method of determining the release point has many advantages, it retains two of the inherent disadvantages of the Norden optical sight as well as those inherent in the reduced resolution of the radar system. These are the necessity of a long straight bombing approach and the limitation of the sighting angle to angles less than 70 degrees, in order to synchronize the rate end. Improvements in antiaircraft radar fire control and the use of proximity fuses will make obsolete any bombing computers requiring a straight and level approach. Moreover, the increased speed of future bombing aircraft will reduce drastically the time on the bombing run, particularly if the maximum sighting angle is only 70 degrees. A 70-degree sighting angle corresponds to approximately 11 miles ground range for an airplane at 24,000 ft, while bombs are dropped at about 3 miles ground range at ground speeds of about 180 mph. Thus, the release point problem must be solved while the airplane is traveling a distance of 8 miles. When the ground speed of the airplane is 180 mph, 8 miles corresponds to a time interval of 160 sec (which is acceptable). If the ground speed were tripled, the time available for synchronizing on the target would be far from adequate. The obvious immediate answer to this difficulty is to modify the rate end so as to permit greater sighting angles. A mechanical modification to permit such an increase has been constructed at the Armament Laboratory at Wright Field.

Nosmo and similar hybrid products of radar and optical bombing systems were developed as interim bombing methods. A better bombing computer would take advantage of the greater range and range accuracy that radar systems can provide as compared to optical systems. The AN/APA-5, MX-344, and GPI computers described in subsequent sections are all attempts to take advantage of these qualities of radar systems. While the Nosmo method of solving the rate problem has been superseded by these newer computers, the Nosmo method of determining a course to bring the ground track of the airplane through the target is novel and still useful.

8.4 LOW-ALTITUDE BOMBING COMPUTERS

8.4.1 General Principles of Low-Altitude Bombing Computers

The tactical use of radar search systems employed in antisubmarine activities during the early part of World War II was limited by the lack of suitable radar bombing methods. It was evident that a low-altitude radar bombsight would find wide applications not only against submarines but also in night attacks against enemy shipping. In the spring of 1942, therefore, an experimental bombing attachment for basic search radars and the Norden sight was developed which, because of its low-altitude operational limit, was commonly called *low-altitude bombing* [LAB]. The basic features of this experimental model were later incorporated into production equipments, the AN/APQ-5 and the AN/APA-5, sometimes referred to as the LAB Mk I and LAB Mk II respectively.

Actually the term LAB, as commonly used, denotes systems derived from the Radiation Laboratory experimental LAB, but which are not necessarily limited to low-altitude operation. They are bombing attachments and require that the basic radar system furnish only the synchronizing trigger, video signal, and azimuth reference data. The normal operation of this basic radar and the Norden sight is not impaired. A list of the search radars which may be used in combination with LAB computers includes the SCR-517, SCR-717, AN/APQ-13, AN/APS-15, and AN/APS-10. Since LAB equipments obtain video signals from the basic radar, the resolving capabilities of these radars are a factor affecting the bombing accuracy and type of target against which the equipment may be employed. The low-altitude limit of the experimental LAB and the AN/APQ-5 generally confines their use to isolated targets. The AN/APA-5 and the AN/APQ-5B contain provisions for extending the operating altitude, permitting their use against any target which can be resolved on the bombardier's indicator.

Fundamentally, the operational principles associated with LAB are analogous to those of the Norden sight. This similarity is desirable for two reasons; first, the basic philosophy of the Norden sight has been well proved, and second, the training of LAB bombardiers, who have had previous Norden sight experience, is simplified.

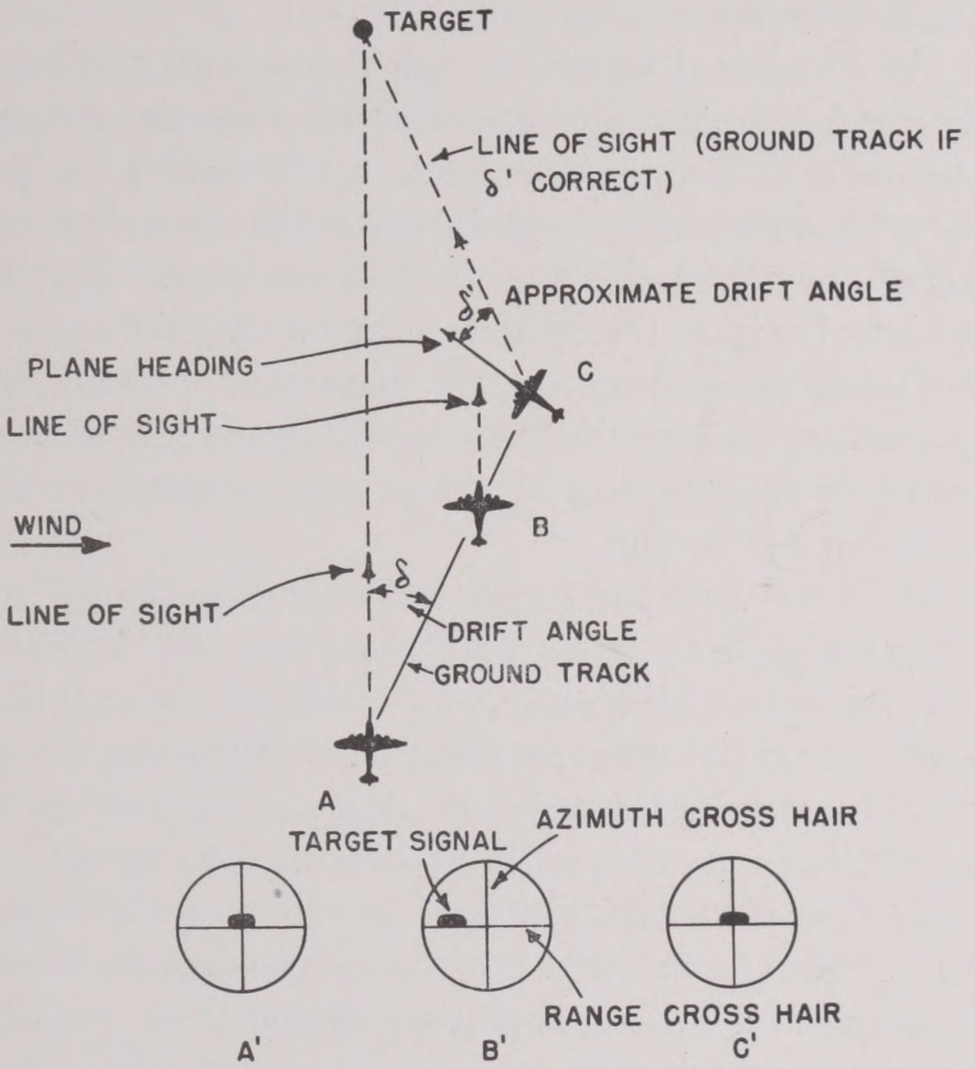
As in optical bombing, the duties and responsibilities of the navigator and bombardier are clearly defined. The navigator guides the aircraft to the target area and the bombardier takes control of the plane only after sighting the desired target. This division of responsibility allows the bombardier to concentrate exclusively on the necessary preliminary procedures before the start of the bomb run, as well as to devote full time to the process of synchronization during the run.

All LAB systems employ the same technique for steering to the release point, and furnish the bombardier with a similar type of indicator presentation during low-altitude operation. A B scope (see Chapter 7), mapping 10 miles in range and expanded in azimuth, is used for initially locating the target.

During the tracking procedure, the target is viewed on a 1-mile expanded portion of the search sweep. Centered on this expanded indication is an azimuth and range cross hair.

A potentiometer or selsyn tie-in between the radar scanner and the Norden azimuth stabilizer makes the azimuth cross hair correspond with the azimuth of the Norden telescope. The bombardier, by operating the azimuth stabilizer knobs in the usual manner, steers the plane to the proper release point by synchronizing the target on this azimuth cross hair. Figure 7 illustrates this method of steering and the target position for the conditions of this approach. The method of establishing a collision course is identical with that used in the Norden sight. Target drift with respect to the azimuth cross hair is more readily detected on the expanded sweep than on a conventional PPI. The tie-in between the azimuth stabilizer and the radar scanner stabilizes the indicator presentation against yaw of the aircraft, but not against pitch or roll.

The expanded portion of the search sweep used for target tracking purposes is continuously varied in range as the target is approached. The range rate and the displacement of this moving sweep are adjusted by knobs, similar to those on the Norden bombsight, until the target remains positioned on the range cross hair. If the range synchronization is exact, the target remains stationary on the bombardier's indicator. With such an expanded stationary presentation, the blurring of moving signals by the persistence of the indicator is eliminated. The expansion of the target area on the bombardier's indicator aids in positioning the tracking line and in identifying complex targets. The slant range velocity is determined by this range synchronization procedure and is entered into a range computer. The range computer positions a release signal at the proper slant range for the conditions in the bomb run. Bomb release is automatic, occurring when the slant range of the tracking line and the release signal are equal.



A'. Scope presentation with aircraft at *A*. Aircraft heading and line of sight to the target coincide. Target appears centered on azimuth cross hair. *B'*. Scope presentation with aircraft at *B*. Aircraft heading and line of sight same as at position *A*. Target is left of the line of sight and therefore appears to the left of the azimuth cross hair. *C'*. Scope presentation with aircraft at *C*. Aircraft has been turned by azimuth course knob until target is centered on azimuth cross hair. Line of sight and aircraft heading still coincide. Aircraft heading is then changed by adjustment of drift knob through an additional approximated drift angle. Target remains centered on azimuth cross hair during adjustments of the drift knob because of stabilized line of sight.

FIGURE 7. LAB method of steering and indicator presentation.

The range computers are different in the various LAB systems and are discussed below.

8.4.2 AN/APQ-5

The basic principles of the experimental LAB were incorporated in the production of AN/APQ-5.[86] This equipment played a major role in night attacks on Japanese shipping in the southwest Pacific after its first combat introduction in the fall of 1943, and established an impressive combat record.[76a] One report [71] revealed that during the 4-month period from December 1943 to April 1944, one squadron equipped with AN/APQ-5 sank 47 per cent of the total tonnage sunk by its Bomber Command and in doing so, utilized only one-fifth of the planes, bombs, and personnel employed by that command in attacks against enemy shipping. The use of the AN/APQ-5 and a second version of this equipment, called the AN/APQ-5B, was continued by the Army Air Forces until the termination of hostilities.

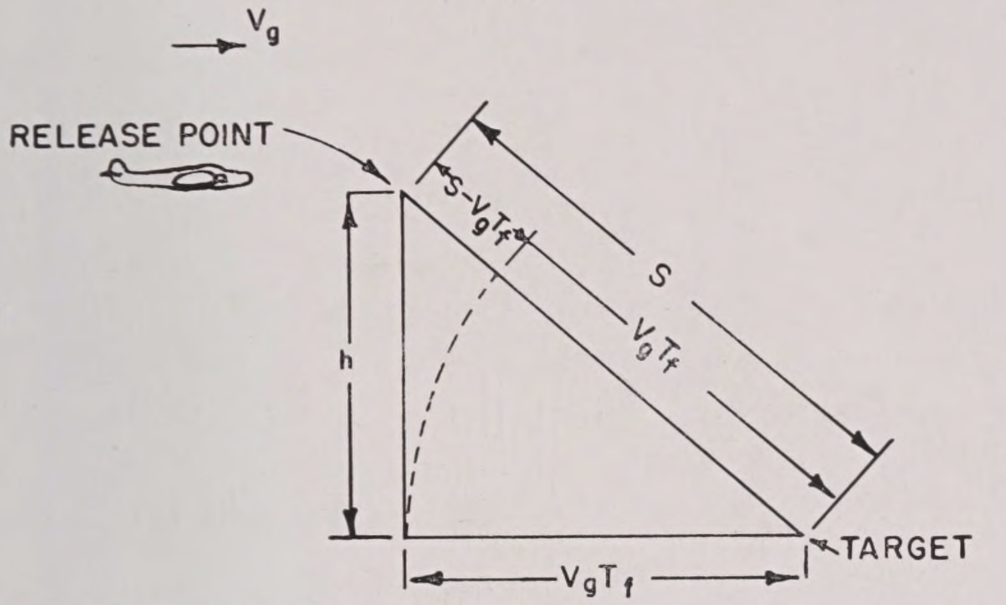
AN/APQ-5 Range Computer

This section will be devoted to a description of the AN/APQ-5 range computer and to the solution of the tracking and release triangles. This computer was designed for operation at altitudes between 65 and 2,000 ft. The range tracking procedure is not truly synchronous since the range synchronization procedure measures rate of change of slant range (slant-range velocity), not true ground speed (rate of change of ground range). As a result, the slant-range velocity must be determined early in the run where the slant range and ground range are nearly equal. Once the range rate has been determined, any drift of the target from the range cross hair is corrected by use of the range displacement knob only. During the later part of the run, the bombardier must continuously reposition the target on the tracking line. If the target is lost because of fading, distortion, or sea return, range errors will result because of the inability of the operator to position the target correctly on the range cross hair.

The slant-range release distance is actually the ground range to the target at release ($V_g T_f$) plus a second distance which is a function of closing speed and altitude. Figure 8 shows the release triangle and includes a derivation of the slant-range release distance in terms of altitude and closing speed. The voltages proportional to

$$\left(k \frac{h^{\frac{3}{2}}}{h^{\frac{1}{2}} + V_g}\right)$$

and ($k' V_g h^{\frac{1}{2}}$) are obtained by means of a resistance computer whose basic circuit is shown in Figure 9. The resistance values of the basic circuits in this figure are proportional to the quantities h and V_g as indicated. No derivation of the resultant voltages will be given, as the application of simple circuit theory will establish the validity of the expressions. The use of ganged potentiometers enables all altitude (h) and closing speed (V_g) data to be entered into the computer with only one dial setting for each quantity. Nonlinear potentiometers are used to provide the exponential functions of h. The output voltages from this computer, plus a third voltage, are combined and are used to position the electronic release index. This third voltage, a slant-range increment voltage, modifies the slant-range release distance to compensate for bomb trail or to permit dropping a number of bombs in train.



S = slant range release distance
V_g = ground speed
h = altitude

$$T_f = \text{time of fall} = \sqrt{\frac{2h}{g}}, \text{ where } g = \text{acceleration of gravity}$$

$$S = \sqrt{h^2 + (V_gT_f)^2} = \sqrt{h^2 + \frac{2hV_g^2}{g}}$$

$$S - V_gT_f = \sqrt{h^2 + \frac{2hV_g^2}{g}} - V_g\sqrt{\frac{2h}{g}}$$

or $S - V_gT_f \cong K\frac{h^{3/2}}{h^{1/2}+V_g}$ (approximation for $2{,}000 > h > 65$
K = constant)

$$S = (S - V_gT_f) + V_gT_f = K\frac{h^{3/2}}{h^{1/2}+V_g} + K'V_gh^{1/2}$$

(K' = constant)

FIGURE 8. AN/APQ–5 release triangle solution.

The altitude is set into this computer on a dial before the bombing run. The closing speed, actually a measure of the slant-range velocity, is entered into the computer automatically by the process of rate synchronization. The slant-range increment is entered on a second dial and is obtained by reference to charts after V_g has been determined.

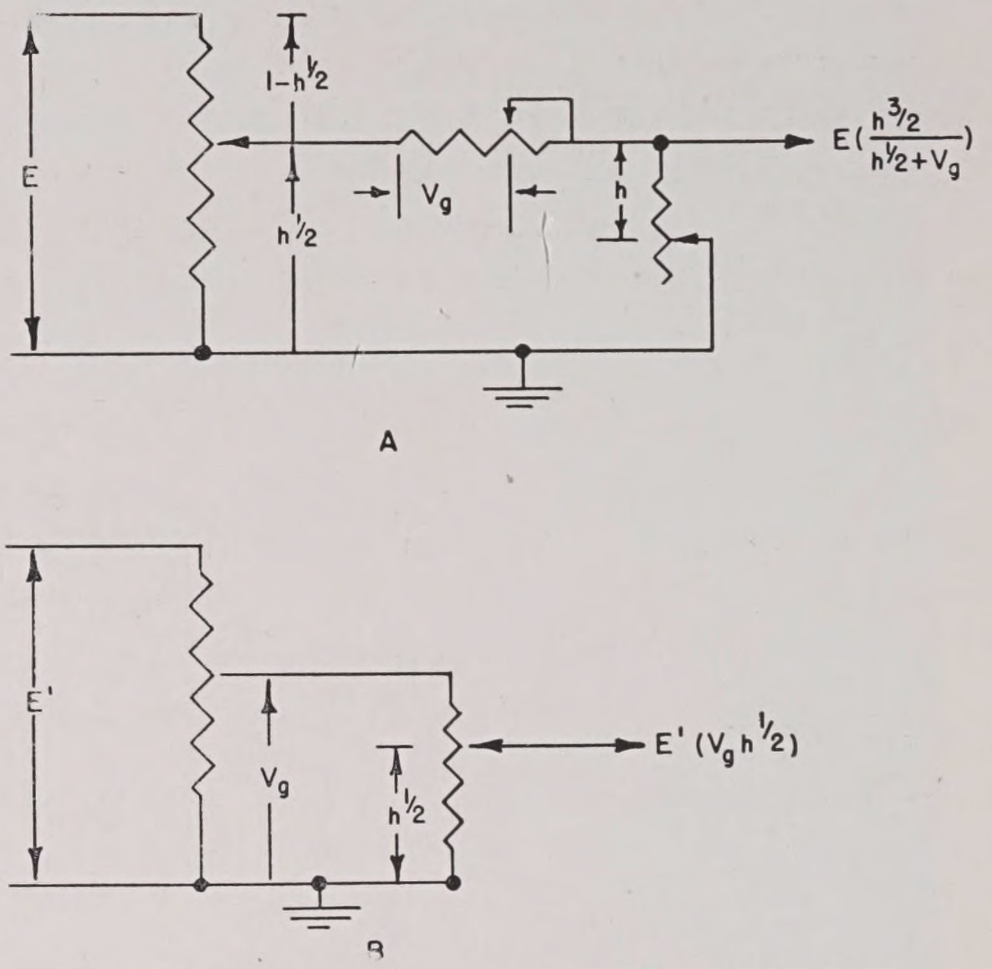


FIGURE 9. AN/APQ–5 range computer circuits.

8.5 COMPLETELY SYNCHRONOUS COMPUTERS

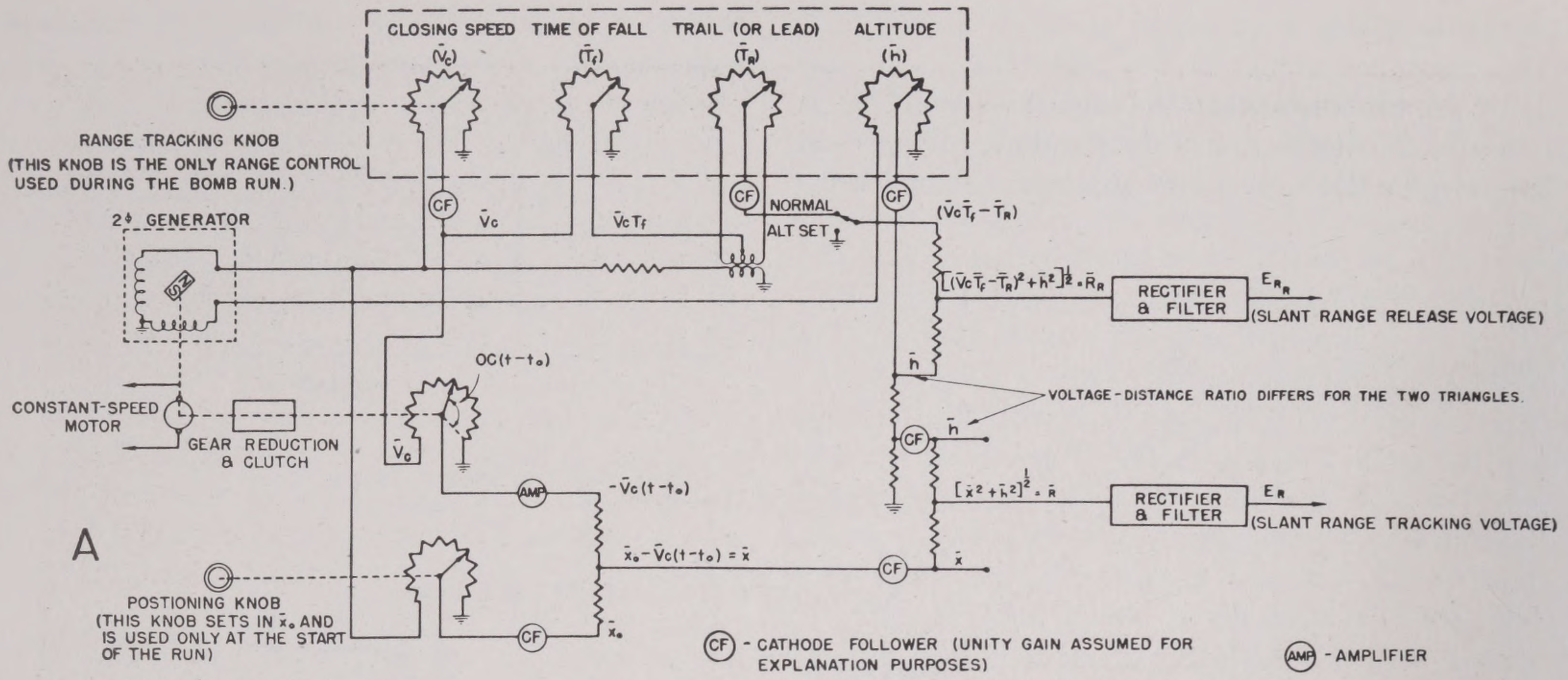
8.5.1 AN/APA-5

GENERAL DESCRIPTION

The AN/APA-5, or LAB Mk II, is a completely synchronous general purpose bombing attachment capable of operating at altitudes from less than 1,000 ft up to 30,000 ft or more.[99] Although the complete altitude range is covered by two overlapping scales, the operational procedures on each scale are identical. All necessary data, obtained from standard aircraft instruments and bombing tables, are entered on computer dials before the run is begun. Once the bombardier has started the run, his only operation is to keep the target on his range and azimuth cross hairs. No further reference to tables is required. The process of range synchronization establishes the true ground speed which is automatically entered into the computer. The solution of the slant-range release distance is automatic and involves no approximations. Range tracking is completely synchronous and extrapolated releases are possible from any point during the run.

AN/APA-5 OPERATION

The method of steering to the release point has already been discussed in Section 8.4.1.[37] The range


CLOSING SPEED ($\bar{V}_c$)
TIME OF FALL ($\bar{T}_f$)
TRAIL (OR LEAD) ($\bar{T}_R$)
ALTITUDE ($\bar{h}$)
RANGE TRACKING KNOB (THIS KNOB IS THE ONLY RANGE CONTROL USED DURING THE BOMB RUN.)
2φ GENERATOR
CF
$\bar{V}_c$
$\bar{V}_c\bar{T}_f$
NORMAL
ALT SET
$(\bar{V}_c\bar{T}_f-\bar{T}_R)$
$[(\bar{V}_c\bar{T}_f-\bar{T}_R)^2+\bar{h}^2]^{\frac{1}{2}}=\bar{R}_R$
RECTIFIER & FILTER
E_{R_R}
(SLANT RANGE RELEASE VOLTAGE)
$\bar{h}$
VOLTAGE-DISTANCE RATIO DIFFERS FOR THE TWO TRIANGLES.
OC$(t-t_0)$
CONSTANT-SPEED MOTOR
GEAR REDUCTION & CLUTCH
$\bar{V}_c$
AMP
$-\bar{V}_c(t-t_0)$
$[\bar{x}^2+\bar{h}^2]^{\frac{1}{2}}=\bar{R}$
RECTIFIER & FILTER
E_R
(SLANT RANGE TRACKING VOLTAGE)
A
$\bar{x}_0-\bar{V}_c(t-t_0)=\bar{x}$
$\bar{x}$
POSTIONING KNOB (THIS KNOB SETS IN $\bar{x}_0$ AND IS USED ONLY AT THE START OF THE RUN)
$\bar{x}_0$
CF - CATHODE FOLLOWER (UNITY GAIN ASSUMED FOR EXPLANATION PURPOSES)
AMP - AMPLIFIER

x = ground range to target
h = altitude of plane relative to target
R = slant range to target
R_R = slant release range
x_0 = ground range to target at time tracking is started
t = time

t_0 = time at which tracking is started
V_c = closing speed (velocity of airplane relative to target)
T_R = trail (distance by which bomb lags airplane at time of impact)
T_f = time of fall of bomb
$\bar{x}$, $\bar{h}$, $\bar{V}_c$, etc. are quantities in the computer which correspond respectively to x, h, V_c, etc.

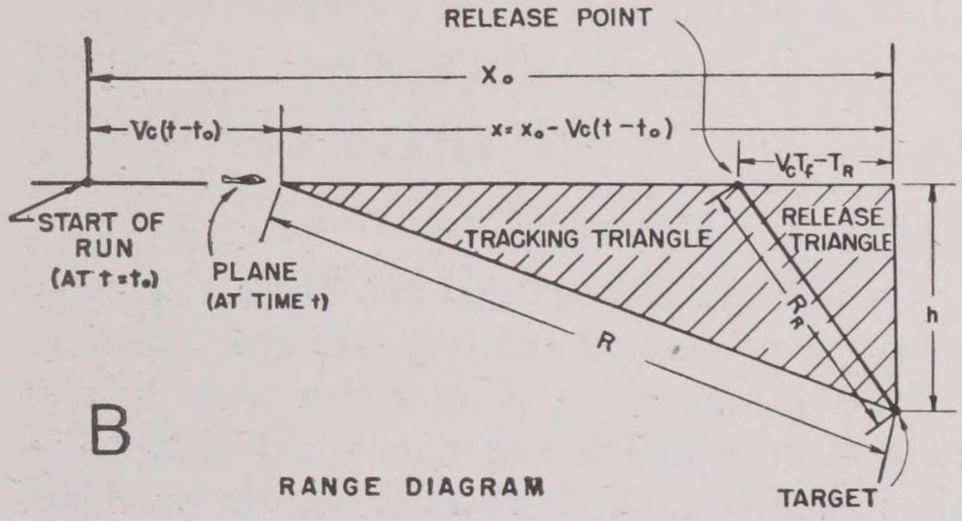

RELEASE POINT
X_0
$-V_c(t-t_0)$
$x=x_0-V_c(t-t_0)$
$V_cT_f-T_R$
START OF RUN (AT $t=t_0$)
PLANE (AT TIME t)
TRACKING TRIANGLE
RELEASE TRIANGLE
R_R
R
h
B
RANGE DIAGRAM
TARGET

FIGURE 10. Operation of AN/APA-5 range computer.

scales depicted on the bombardier's scope when used for search and tracking are 10 miles and 1 mile respectively during low-scale operation. These scales are identical with those of the AN/APQ-5. When the slant-range release distance exceeds 5,000 ft, the high-altitude scale of the range computer must be used, which changes the indicator sweep to 30 miles for searching and 3 miles for tracking. The operating scales are readily changed by switches on the control box. On both the low- and high-altitude scales, the operational procedure is the same.

Figure 10 is a simplified diagram of the AN/APA-5 computer and a diagram of the tracking and release triangles. Figure 11 is a photograph of an AN/APA-5 installation in a B-24 airplane. During low-scale operation, the maximum readings of the four computer dials are closing speed, 400 miles per hour; time of fall, 15 sec; trail (or lead), 500 ft; and altitude, 5,000 ft. These maximum values during high-scale operation are 400 miles per hour, 50 sec, 5,000 ft, and 50,000 ft respectively. The exact solutions of the tracking and release triangles are obtained by two electrical triangle solvers which determine the vector sum of two quadrature sinusoidal voltages obtained from the two-phase generator. One of the sinusoidal voltages is proportional to the ground-range leg of the tracking and release triangles, the other to the altitude leg. These alternating voltages are combined in a resistance network and rectified, the d-c output of the two rectifiers determining the position of the tracking index and the release index on the scope.

Before the run, the altitude, determined from standard aircraft instruments or the radar system, and the time of fall and trail, obtained from standard bombing tables, are entered on the computer dials. The range synchronization procedure automatically adjusts the closing-speed dial to the true closing speed, thereby eliminating the necessity for presetting this information. The target is synchronized on the range cross hair during the tracking operation by a single knob control which adjusts the closing-speed dial. By referring to Figure 10 and the discussion below, the theory of this single knob range track-

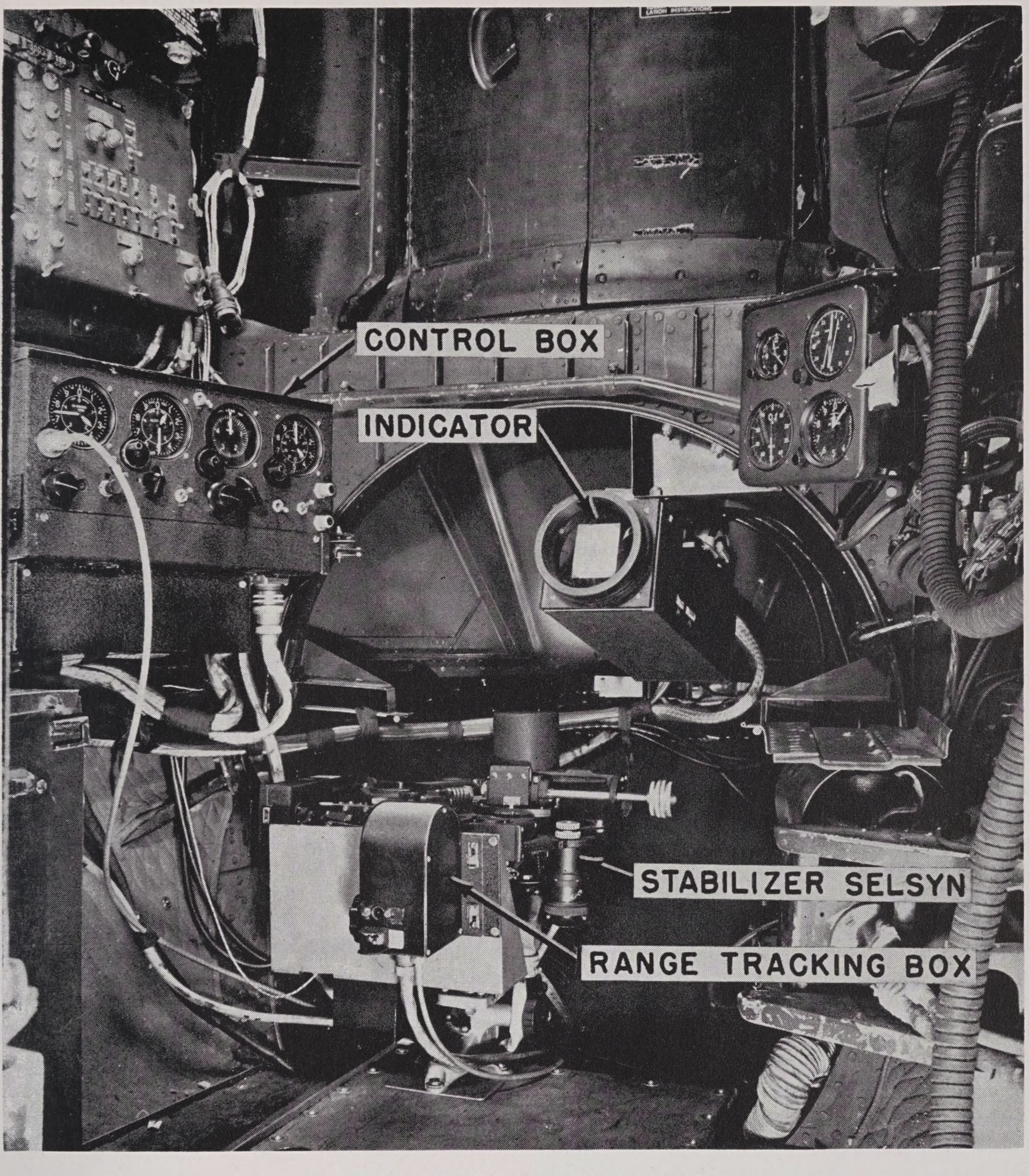


FIGURE 11. AN/APA–5 installation in B–24D.

ing is apparent. At the instant range tracking is started by engaging the clutch between the constant speed motor and the tracking potentiometer, the initial ground range voltage ($\bar{x}_0$) begins to decrease at a linear rate depending on the setting of the $\overline{V}_c$ dial. At any time (t), the value of $V_c(t - t_0)$, the ground range distance traveled since the start of the tracking operation, must be equal to $\overline{V}_c(t - t_0)$ if the target is to remain on the cross hair. If V_c is not equal to $\overline{V}_c$, the target will appear to drift away from the cross hair. Repositioning the target with the range tracking knob equates $\overline{V}_c$ to V_c. Once $\overline{V}_c$ is correctly determined, the tracking is completely synchronous during the remainder of the run.

Evaluation

The AN/APA-5 first became available in February 1945, but because of the magnitude of the installation and training program, was not introduced into combat before the end of the war. Several flight-test programs were conducted in the summer of 1944 using a preproduction AN/APA-5 and an AN/APQ-13.[42–44] A series of 40 bomb runs were made against a point target at each of three altitudes, 1,000, 5,000, and 15,000 ft. A summary of the results of these tests is shown in Table 1.

Table 1. AN/APA-5 test results against point target.*

Altitude (ft)	Range error	Azimuth error	Radial error
1,000	46 (ft)	28 (ft)	63 (ft)
5,000	33 (mils)	19 (mils)	40 (mils)
15,000	10 (mils)	10 (mils)	14 (mils)

* All errors are probable errors about the target center, that is, 50 per cent of the total runs were within the error shown.

Army Air Forces Board tests, using Army personnel, were conducted against two complex targets, the H. J. Kaiser Company plant, Fontana, California, and the North American Aircraft Corporation, Inglewood, California. Runs were scored by a photo-theodolite (see Section 13.1.2). A total of 55 runs was made against the Kaiser plant at 15,000 ft altitude and 50 per cent of the total runs were within 17 mils of the target center. Against the North American Aircraft Corporation from this same altitude, a probable error of 22 mils was obtained for a total of 50 runs. These errors were measured from an arbitrary target center, chosen before the runs were begun.

The completely synchronous range computer, coupled with the 3-mile expanded sweep used during the high-altitude tracking operation, contributes greatly to the successful use of the AN/APA-5 against complex targets. The radar pictures of complex targets have a tendency to break up and become badly distorted at the end of the bomb run. The synchronous range tracking of this equipment permits extrapolated releases from distances where this distortion is small. The wide operational limits of the AN/APA-5, plus the completely synchronous solution of the bombing problem, make it a versatile system adaptable for many tactical purposes.

8.5.2 MX-344 Computer

General Description

Although the bombing computer to be described briefly in this section was developed by the Bell Telephone Laboratories, rather than the Radiation Laboratory, any discussion of computers for radar mapping equipments would be incomplete without the inclusion of a section on the AN/APQ-13, Mod. II, or, as it was officially known, the MX-344 computer.[81a]

The MX-344 computer was designed to be operated by the regular radar operator, although it could conceivably be operated by the bombardier or by the navigator. Its size, however, practically rules out operation by the bombardier. The main controls of the computer are exactly analogous to those on the Norden bombsight as there are two sets of knobs (which may be double gripped), one set controlling ground range and ground speed, the other set controlling turn and drift. Bomb ballistics, in the form of time of fall, trail, and altitude, are set in on conveniently calibrated dials.

Despite the similarity of controls, however, the MX-344 has two advantages over the Norden sight as a bombing computer. In the first place, tracking of the target may always be started when it is still approximately 15 miles away, since the tracking circuits are dependent on time-to-go to the target rather than on the sighting angle to the target, as is the case for the Norden sight. This means that low-altitude runs are not handicapped by requiring the sight to be synchronized in a much shorter time than high-altitude runs. The second advantage of the MX-344 over the Norden and one of its most important features is that it easily permits offset of the aiming point from the target. The limitations on the offset are that the aiming point must be within 10 miles of the target and a course should be chosen which lies with ± 60 degrees of the bearing of the target with respect to the aiming point. Other courses may be chosen, but the accuracy will be somewhat reduced.

Among the strictly radar features of the computer is the provision of continuous sweep expansion so that the point under the cross hairs is held at a fixed position on the PPI. This is of considerable importance in high-speed planes where the motion of the returns on a high-persistence PPI can cause blurring of the picture, but the continuous sweep expansion may lead to certain tracking errors because of the variation in operator judgment when different sweep speeds are used. Two other desirable features are (1) a longer double-gripping time constant between the range and rate knobs which is better adapted to radar than the Norden time constant of approximately 10 sec, and (2) a method of giving sighting angle information to the Norden operator, so that even when he cannot see the target he can still synchronize his sight and thus be prepared to take advantage of any break in the undercast.

The operation of the MX-344 introduces no technique essentially different from those involved in the operation of the AN/APA-5 or AN/APQ-5 computers except in so far as the radar operator is also expected to operate the computer. While navigating to the target area, the operator will set in the time of fall and the trail ratio for the briefed altitude and airspeed. He will also set in the offset range and bearing of the target from the aiming point, which will have been previously computed and given to the operator at the briefing, prior to the mission. On reaching the target area, the operator has two main tasks: identifying the aiming point and synchronizing the cross hairs on this point. The identification of the aiming point has been discussed in Chapter 6. It is sufficient to say here that, since an offset aiming point may be used, a point easy to identify should be chosen.

In order to synchronize the cross hairs on the aiming point, the operator must first set an accurate altitude into the computer. This is done with the altitude knob, by making a range circle coincide with the first ground return on the PPI. In order to facilitate this measurement, the computer is arranged so that when the operator pushes in on the altitude knob, the sweep speed of the PPI is increased with the result that the first ground return is out near the edge of the PPI. After setting in the altitude, the operator synchronizes the azimuth marker on the aiming point by using the turn and drift knobs, and then synchronizes the range circle on the target with the range and ground speed knobs. Actually, these last two operations are not independent and should be performed more or less simultaneously. This interdependence between the range and azimuth synchronization is undesirable, but is inherent in the MX-344 computer because of the method in which it solves the bombing problem.

Azimuth Solution. The azimuth portion of the bombing problem is illustrated in Figure 12. The true bearing to the aiming point is designated A and the true bearing to the target displaced by crosstrail is designated ψ, this latter being the desired ground track. The difference $A - \psi$ between these two angles is called α. The true bearing of a line extending from the aiming point to the target is β, and the difference $(\psi - \beta)$ between this bearing and the desired track is θ. With a drift angle, δ, the desired heading of the plane, γ, is $(\psi - \delta)$.

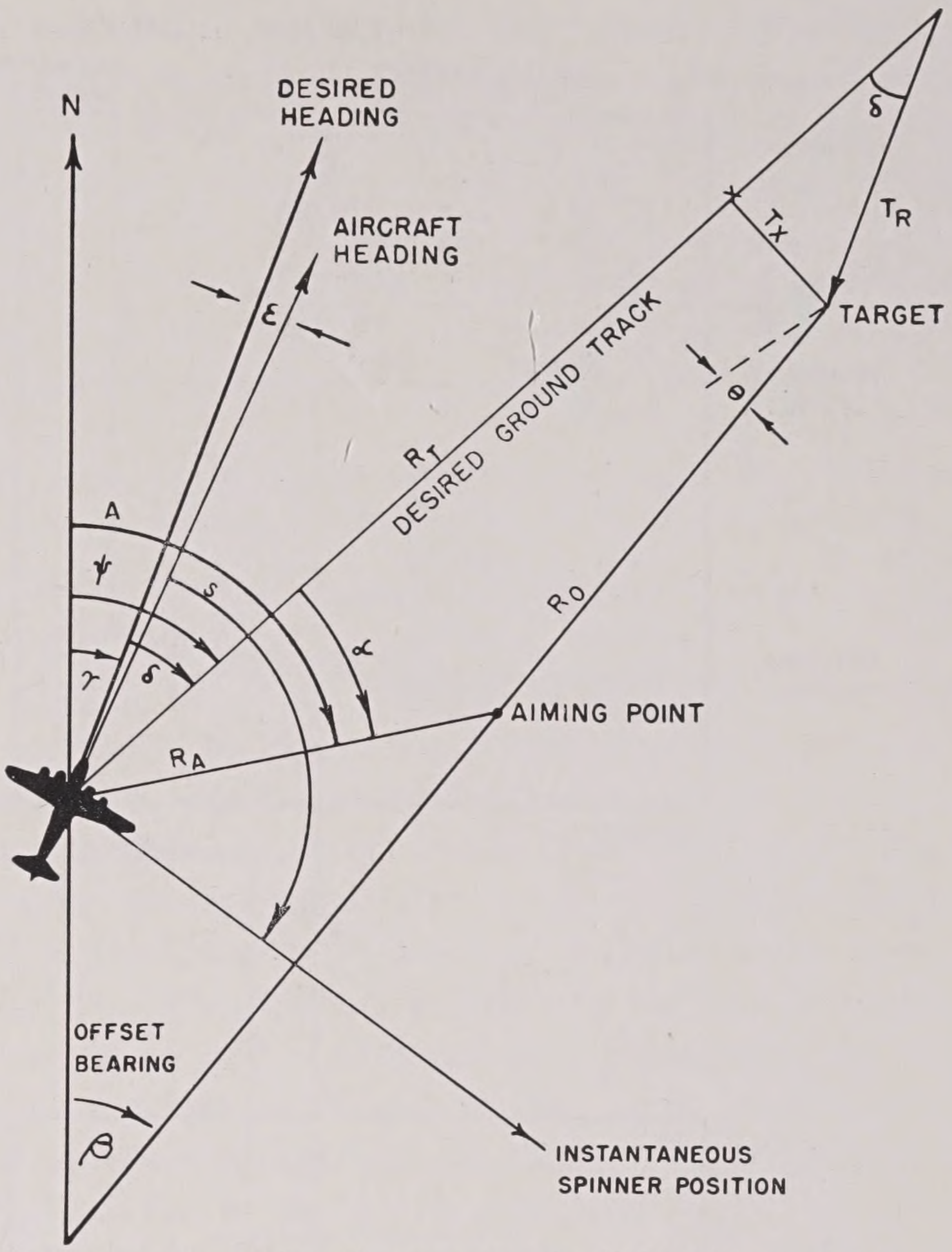


FIGURE 12. Azimuth geometry for MX-344 computer.

The angle α is determined from the relationship

$$R_A \sin \alpha - T_R \sin \delta = R_0 \sin \theta$$

where T_R is the trail, R_A is the ground range to the aiming point, and R_0 is the offset ground range (from aiming point to target).

The desired heading γ for the airplane is given in terms of the bearing to the aiming point by

$$\gamma = A - \alpha - \delta.$$

Figure 13 is a block diagram of the computer. Voltages are represented by solid lines, while mechanical connections are shown as broken lines. An examination of the part of Figure 13 labeled "Azimuth" indicates how the course of the aircraft is determined. A voltage that is proportional to the flux gate compass reading is connected to a torque unit. The torque unit is geared to a mechanical differential,

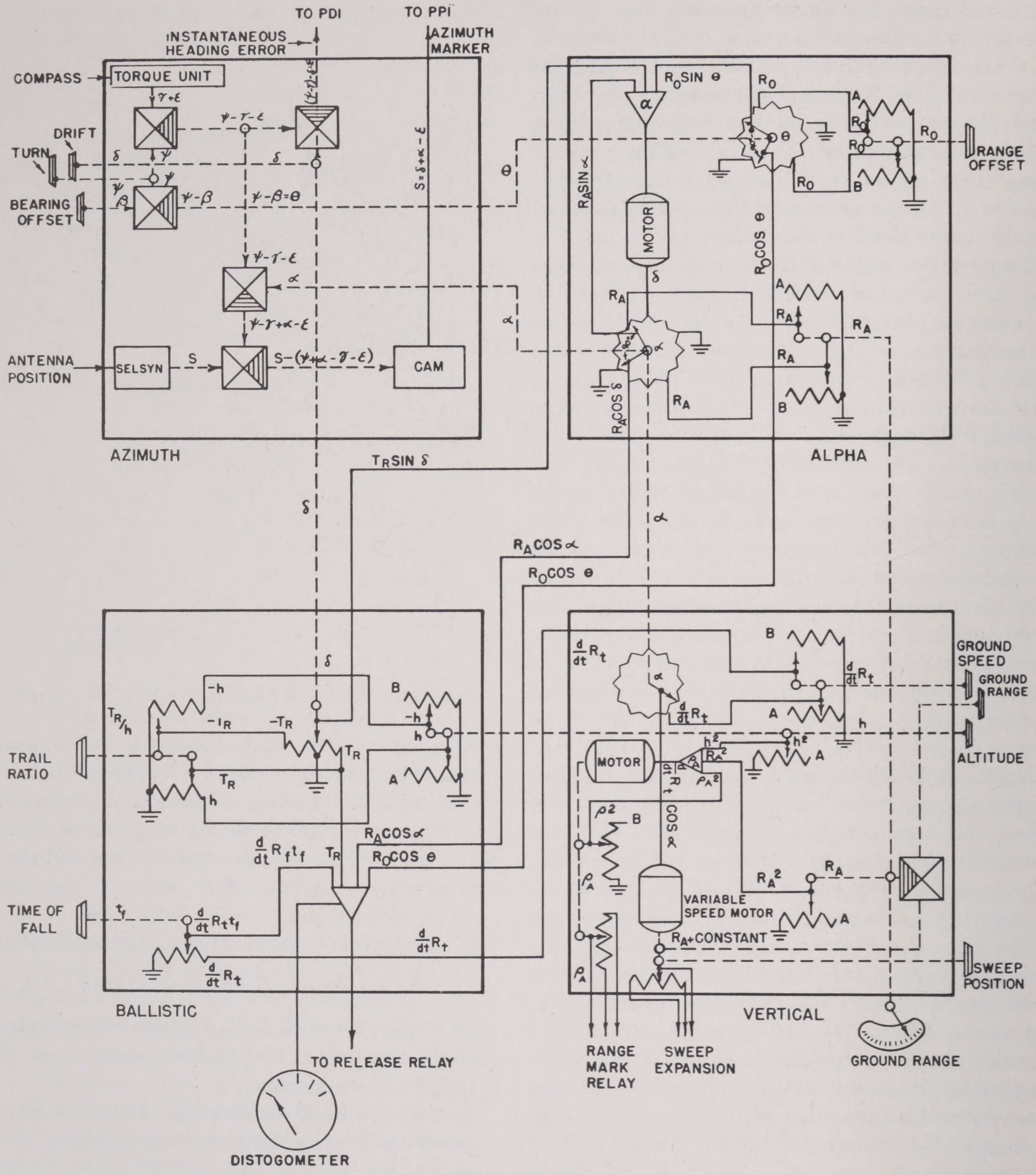

TO PDI
TO PPI
INSTANTANEOUS HEADING ERROR
AZIMUTH MARKER
COMPASS
TORQUE UNIT
DRIFT
TURN
BEARING OFFSET
ANTENNA POSITION
SELSYN
CAM
AZIMUTH
RANGE OFFSET
MOTOR
ALPHA
TRSIN δ
RACOS α
ROCOS θ
TRAIL RATIO
TIME OF FALL
BALLISTIC
TO RELEASE RELAY
DISTOGOMETER
GROUND SPEED
GROUND RANGE
ALTITUDE
VARIABLE SPEED MOTOR
RA+CONSTANT
SWEEP POSITION
VERTICAL
RANGE MARK RELAY
SWEEP EXPANSION
GROUND RANGE

Figure 13. Block diagram of MX–344 computer.

whose second input is the turn control. The output from this differential is fed to another differential, the second input to which is the drift control. Thus the output of this second differential represents the instantaneous error ϵ in the heading of the airplane and can be used to provide *pilot's direction indicator* [PDI] information and to control the automatic pilot. The mechanical differential, to which the bearing offset knob is connected, receives as a second input the rotation of the turn control and thus the output of the differential is seen to be equal to θ when the PDI reads zero.

A steerable electronic marker is obtained from a cam mechanism. The cam is driven by a mechanical differential whose output corresponds to $S - (\psi - \gamma + \alpha - \epsilon)$. The two inputs to the mechanical differential are the position of a selsyn motor repeating the antenna position S, and a second mechanical differential output corresponding to $\psi - \gamma + \alpha - \epsilon$. (The means of obtaining the shaft rotation α will be discussed later.) Thus, when the azimuth marker is made to pass through the aiming point and the PDI reads zero, the aircraft will fly the proper course γ.

Vertical Triangle Solution. The vertical triangle to be considered is shown in Figure 14 where h is the altitude, R_A the instantaneous ground range to the aiming point, and ρ_A the instantaneous slant range to the aiming point.

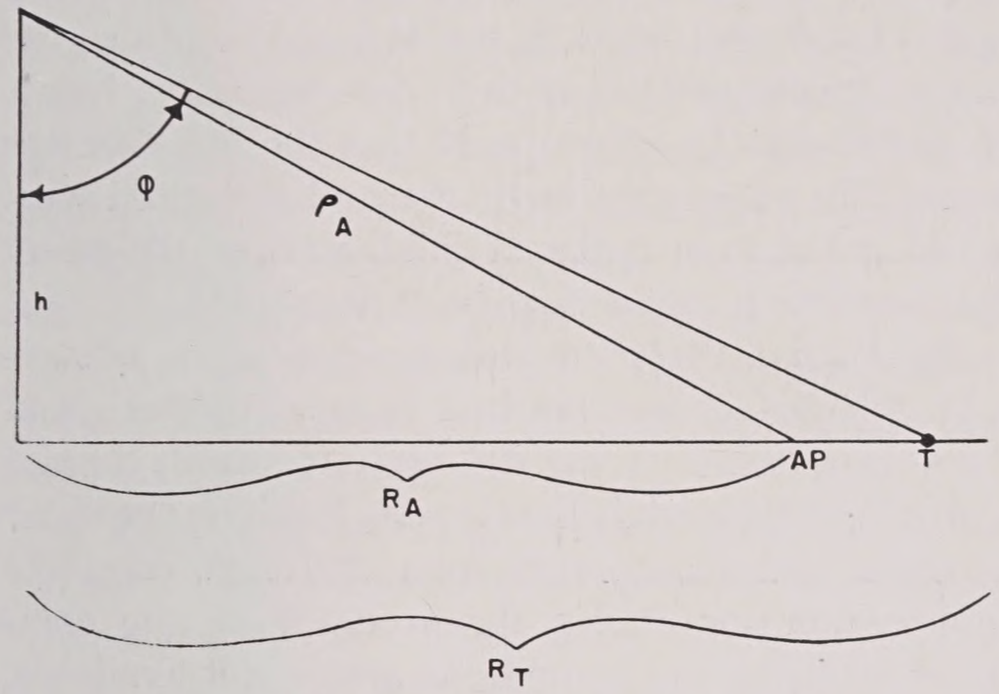


FIGURE 14. Vertical geometry for MX-344 computer.

Referring again to Figure 13, in the section labeled "Vertical," the ground speed knob controls a double potentiometer which is connected to a cos α potentiometer which converts ground speed into its component in the direction of the aiming point. The voltage proportional to this component controls a variable speed motor which drives a shaft at the proper rate for tracking the aiming point. This shaft drives a sweep expansion potentiometer and also is one input to a mechanical differential, the other input being from the ground range knob. The output of this differential, which, when synchronized, gives continuously the varying ground range to the aiming point, drives a square-law potentiometer for the vertical triangle solution, and is also used in the Alpha computer, as described below. The altitude knob drives a square-law potentiometer for the vertical triangle solution and also a dual potentiometer in the ballistic computer.

The outputs of the two square-law potentiometers mentioned above are combined in a servo-amplifier which controls a servo-motor to make $\rho_A^2 = h^2 + R_A^2$, where ρ_A^2 is derived from a third square-law potentiometer driven by the servo-motor. The motor also drives a linear potentiometer from which is derived the proper voltage for controlling the range mark delay circuit.

Ballistic Computation. The ballistic computation is based on the following relationship at the correct bomb release time.

$$R_A \cos \alpha + R_0 \cos \theta = V_g T_f - T_R = \left(\frac{d}{dt} R_T\right) - T_R$$

where R_T is the instantaneous ground range to the release point.

One of the input controls of the section labeled "Ballistic" in Figure 12 is proportional to the trail ratio, i.e., trail divided by altitude, and drives a double potentiometer which is excited by another double potentiometer driven by the altitude shaft. Thus the output of the first potentiometer is the trail T_R. This output is fed into the bomb release mechanism and is also fed to a potentiometer, the arm of which is driven by the drift knob in the azimuth computer, and the output, $T_R \sin \delta$, (cross trail), is fed to the Alpha computer.

The time-of-fall input to the ballistic computer drives a potentiometer, the voltage on which is proportional to the ground speed. The output $(dR_T/dt)T_f$ is fed to the bomb release mechanism which evaluates the sum of the various input voltages. The other two inputs to this mechanism, $R_0 \cos \alpha$ and $R_A \cos \theta$, are obtained from the Alpha computer as described below.

Alpha Computation. As described previously, α is determined from the relationship,

$$R_A \sin \alpha - T_R \sin \delta = R_0 \sin \theta.$$

The solution is performed by a servomechanism, the inputs to which are the three terms of the equation and the output is a shaft rotation proportional to α. $R_A \sin \alpha$ is obtained by applying a voltage proportional to R_A to a sinusoidal potentiometer driven from the output shaft of the servo. $T_R \sin \delta$ is obtained from the ballistic computer as described above. $R_0 \sin \theta$ is obtained by applying a voltage proportional to R_0 to a sinusoidal potentiometer driven by the θ shaft from the azimuth computer. The range offset knob drives a dual potentiometer to supply the R_0 voltage, and the R_A shaft from the vertical computer does the same for the R_A voltage.

The other outputs from the Alpha computer, $R_0 \cos \theta$ and $R_A \cos \alpha$, are derived from the θ and α

potentiometers by using another sliding contact on each, 90 degrees away from the sine contact.

EVALUATION

The MX-344 represented a definite advance in bombing computer design. Although it was late in appearing on the scene, it would have seen extensive and valuable use in the Pacific theater had not the war ended just when it did. Considering that approximately 70 per cent of the bombing done by the 20th Air Force was radar bombing and considering all the shortcomings of even the sighting angle extension of the impact-predicting computer, the value of the MX-344 was very evident.

The fact that the MX-344 provides offset features should also be considered in evaluating the computer. Although at first glance the offset feature might appear to be the most important feature of the computer, several aspects of the problem must be considered. In the first place, although at the time of the Japanese surrender it appeared that most of the targets remaining to the 20th Air Force could only be attacked by radar by the use of an offset aiming point, it was not demonstrated that these targets had satisfactory offset aiming points. Indeed, our knowledge of the value of offset bombing is based almost entirely on theory. Secondly, the MX-344 increases the maintenance problem. Not only is the computer itself complex, but also in order to obtain satisfactory results with it, the flux gate compass must be maintained at a high degree of accuracy. Indeed, the compass is most probably the limiting factor on the bombing accuracy that may be obtained. The compass problem is discussed in Chapter 9.

Some improvements in the MX-344 are possible. For example, the single knob range tracking, such as used in the AN/APA-5 or the GPI, appears to be definitely superior to the double-gripping arrangement of the MX-344. Likewise, some provision might have been made in the MX-344 to utilize the pulse doppler method of drift determination, but it should always be remembered that the MX-344 was essentially an interim computer and the speed with which it had to be designed and built ruled out many features which might have been desirable.

By August 1945, the theater installation of several MX-344 computers had been completed, and the theater reaction was definitely favorable despite the bulk and the additional burden it put on the radar operator and maintenance man. Although complete information concerning the accuracy of the computer on point and complex targets is not available, preliminary tests without offset indicate an improvement of at least a factor of 2 over the sighting angle method of using the impact-predicting computer. The results obtained using offset will depend to a large extent on compass maintenance.

Chapter 9

THE GPI BOMBING AND NAVIGATION COMPUTER

9.1 THE FUNDAMENTAL GEOMETRY OF THE GROUND POSITION INDICATOR [GPI]

Ground position indicator [GPI] is a term commonly used to denote systems which indicate continuously the present position on the earth's surface of those vehicles in which they are located. In general, these devices obtain present position by integrating the vehicle's velocity over the time it has been in motion. The position is usually indicated on "present-position" dials as either the distance from a point of origin or as the latitude and longitude of the present position. GPI was designed to work with a radar mapping system. Although GPI can be used as a position indicator for any type of vehicle, it was intended primarily for use as a navigation and bombing computer for aircraft.

In addition to the radar system, GPI requires input data from a true-airspeed meter and a compass. Other data such as altitude and bomb characteristics are set into the GPI computer by the operator. From this information, GPI computes and presents on dials the following quantities:

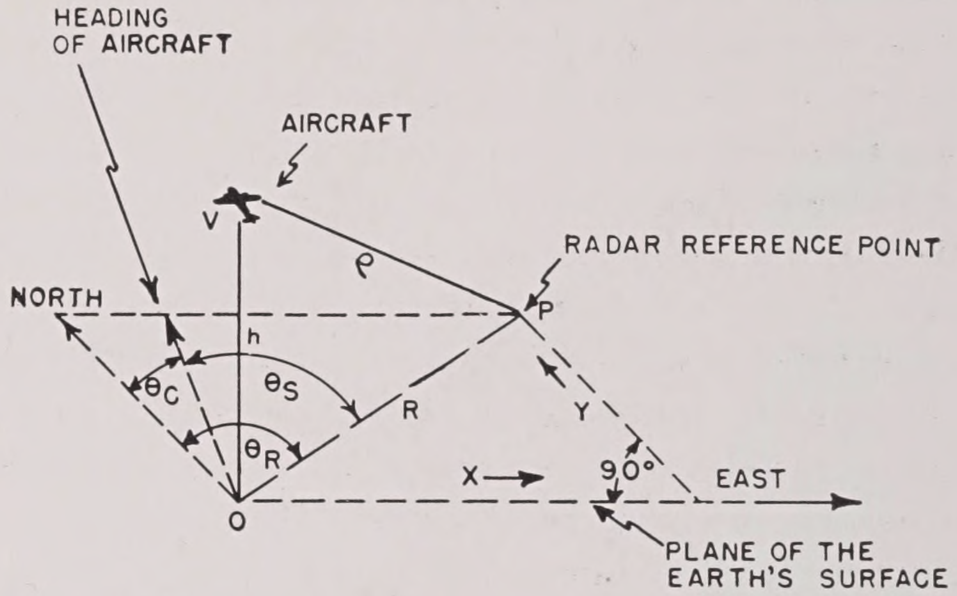
1. Wind, expressed as north-south and east-west components.
2. Altitude.
3. Total distance traveled from some arbitrary origin (such as the base landing field), expressed as north-south and east-west components.
4. Time which will be required to reach a predetermined landmark or reference point, the particular landmark being chosen by making an electronic index (the intersection of a pair of cross hairs on the scope) coincide with the radar signal from the landmark.
5. Position relative to the landmark chosen as in (4), expressed as north-south (Y) and east-west (X) components, i.e., fix data.
6. Heading which must be steered in order to reach the point chosen as in (4) (shown on a *pilot's direction indicator* [PDI]).

In addition to these outputs which the operator can observe, ground speed is obtained, but is fed directly to the integrators without being displayed on a dial.

Fundamentally GPI is a navigational computer. However, bombing can also be done by navigating accurately to a release point and dropping bombs. Therefore, it is only necessary that ballistic data be entered into the computer for the device to become a GPI bombing computer. Since the GPI bombing computer has been designed according to this philosophy, it presents a complete solution to the bombing problem. That is, it solves problems in navigation, identification, computation of the release point, and steering (see Chapter 6).

9.1.1 Fix Determination

The position of the aircraft is established with GPI by measuring (1) the difference in altitude between the aircraft and the reference point (P in Figure 1) which may also be the target, (2) the slant range to the reference, and (3) the direction of the landmark relative to the airplane. The information entering into the determination of fix is shown in Figure 1. First, the value for altitude (h) is set into the computer by the operator, who turns the altitude knob until a range mark coincides with the innermost radar signal appearing on the scope (the ground return or altitude signal). Secondly, the "fix" mileage X and Y dials are adjusted until the cross hairs appear on the radar signal reference, P. When this has been done the dials then show the altitude of the aircraft above the ground and its ground position with respect to the reference. (Ground position is read in rectangular



h = altitude of aircraft
R = ground range aircraft to reference point P
ρ = slant range aircraft to reference point P
θ_C = heading of aircraft
θ_R = direction of reference point P
θ_S = direction spinner points
X = E-W component of R
Y = N-S component of R

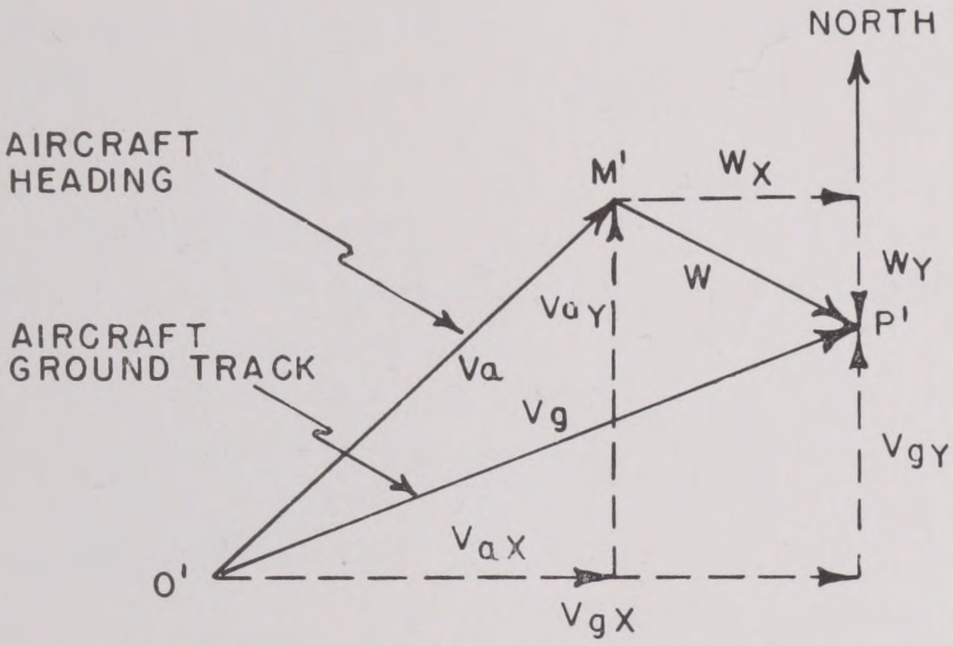
FIGURE 1. GPI geometry of fix.

coordinates on two dials, one corresponding to X miles in the east-west direction, the other to Y miles in the north-south direction.) From this point on, all of the GPI computations are made in a plane parallel to the earth's surface, the altitude (h) factor being used only to convert slant-range radar data into GPI ground-range information.

9.1.2 Rate Determination

The ground rate (velocity) of the aircraft is determined by vector addition of the true airspeed and the wind (see Chapter 6). This vector addition is illustrated in Figure 2.

The components of ground speed $\mathbf{V}_{gx}$ and $\mathbf{V}_{gy}$ are used to control the rate of change in magnitude of X and Y so that the electronic index will move on the radar scope with the same ground speed as the aircraft but in the opposite direction. As can now be seen, if the index is placed over some radar landmark on the radar scope it will remain on that reference provided the values taken for the rates are correct and the coordinate systems used for rate and fix components are the same. If the aircraft should change heading, $\mathbf{V}_{gx}$ and $\mathbf{V}_{gy}$ would continue to represent the coordinate sum of $\mathbf{V}_a + \mathbf{W}$ and the cross hairs would then remain coincident with the radar landmark.



$\mathbf{V}_a$ = true airspeed vector
$\mathbf{V}_g$ = ground speed vector
$\mathbf{W}$ = wind vector
W_X = E-W component of wind
W_Y = N-S component of wind
V_{aX} = E-W component of $\mathbf{V}_a$
V_{aY} = N-S component of $\mathbf{V}_a$
V_{gX} = E-W component of $\mathbf{V}_g = V_{aX} + W_X$
V_{gY} = N-S component of $\mathbf{V}_g = V_{aY} + W_Y$

FIGURE 2. GPI geometry of rate.

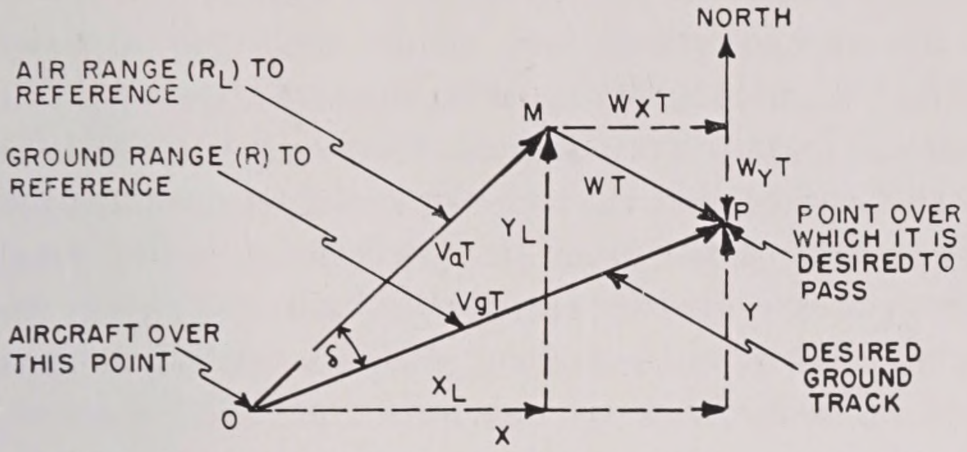
If, at a time when a wind $\mathbf{W}$ is blowing, zero wind is entered into the GPI, it is obvious that the index will not remain coincident with the reference. Rather $\mathbf{V}_{gx}$ and $\mathbf{V}_{gy}$ will represent components of the true airspeed $\mathbf{V}_a$ only and the cross hairs will drift off from the landmark at the rate and in the direction of the wind $\mathbf{W}$. In order that ground rates used by the GPI will be correct, the wind must be entered into the computer. This is done by a process known as memory-point tracking. It consists of making two fix determinations, comparing the ground distance traveled with the air distance (distance relative to the air mass) traveled between the two fixes, and dividing the difference in ground and air distance by the time necessary to accumulate that difference. The actual procedure is very simple as far as the operator is concerned. It consists of placing the electronic index coincident with the landmark signal on the radar scope, pushing a switch, waiting until the electronic mark drifts off the reference, and then resetting it on the landmark. When this process is completed the wind computations are performed by the GPI and the rates which result should cause the marker to remain thereafter coincident with the radar signal.

9.1.3 Course Determination

The course of the aircraft is set by placing the electronic index on the point over which it is desired to fly. This can be done in either of two ways. The first method simply consists of placing the index in coincidence with a signal which can be seen on the radar scope. The second method performs the same function for points which do not appear on a radar scope. The latter method takes advantage of the GPI's knowledge of present position and the operator's ability to set the X and Y dials to desired future position numbers (see Section 9.4.2). Since the X and Y fix mileage dials define the position of the cross hairs, they will appear in the correct position on the radar scope whether a radar signal is there or not.

The geometry of GPI course determination is illustrated in Figure 3 where it can be seen that all factors are known from previous GPI computations except the time T. T represents the time necessary to reach point P at the present airspeed and with the present wind if a heading is taken so that the ground track of the aircraft passes directly through this point.

Triangle POM is similar to the triangle $P'O'M'$ of Figure 2, since their sides are proportional, and the proportionality factor is the time T. Since both $\mathbf{R}$ and $\mathbf{V}_g$ are known, T can be determined if R is divided by V_g or, as in the computer described here, if R_L is divided by V_a. T is indicated on a meter and may be used by the operator to determine his time of arrival at destination.


NORTH
AIR RANGE (R_L) TO REFERENCE
GROUND RANGE (R) TO REFERENCE
M
W_X T
W_Y T
WT
P
POINT OVER WHICH IT IS DESIRED TO PASS
Y_L
VaT
VgT
δ
AIRCRAFT OVER THIS POINT
Y
DESIRED GROUND TRACK
X_L
O
X

This diagram is similar to Figure 2 except that all rates have been multiplied by time T.

T = time necessary to reach reference point P if a correct heading is maintained. $T = R/V_g = R_L/V_a$
$\mathbf{V}_g T = R$ = ground range to reference point P
$\mathbf{W}T$ = distance aircraft is blown in time T
$\mathbf{V}_a T = \mathbf{V}_g T - \mathbf{W}T = \mathbf{R}_L$ = air range to reference point
δ = drift angle

The point M may be considered moving as time T changes; it will coincide with point P at time T equal zero; aircraft always heads toward M to reach point P.

Figure 3. GPI course determination geometry.

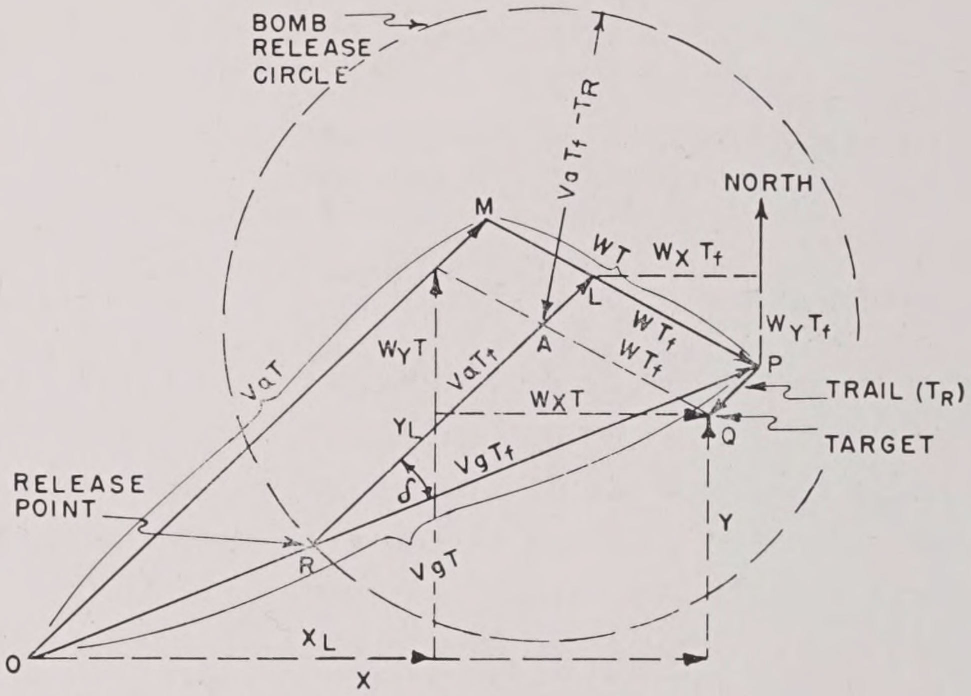
If T is determined in this manner, all the necessary geometrical data for Figure 3 are available in the computer. The computer then can establish the heading OM necessary if the ground track OP is to pass through the point P. This is true only if the cross hairs rest on point P. Having this knowledge, it is then possible to compare present heading as indicated by a compass, with desired heading in the computer, and indicate their difference on a meter. By flying so as to keep the meter indicating zero, the aircraft flies the desired course.

9.1.4 Release and Course Determination for Bombing

The bombing problem can be divided into two parts, direct and offset. Direct bombing consists of releasing bombs so that they hit the target upon which the cross hairs have been placed. Offset bombing consists of hitting a target located a known distance and direction from the reference upon which the cross hairs are placed.

The direct bombing problem involves the same course determination problems as given in Section 9.1.3; however, the release point must be computed. The geometry used for direct bombing is given in Figure 4.

From this figure it can be seen that the release points for the target Q are located on a circle of radius $|\mathbf{V}_a T_f - \mathbf{T}_R|$ and whose center is upwind from the target by $\mathbf{W}T_f$. To reach this conclusion consider the target Q upon which it is desired to drop bombs. A vector **AQ** (equals **LP**) is drawn in the direction the wind is blowing, pointing at Q. If this line represents wind times the time of fall of the bomb, it will represent the distance the bomb is blown while falling. Next a vector **LA** (or **PQ**) is drawn in a direction opposite to the assumed heading of the aircraft. It is given a magnitude equal to the trail $|\ \mathbf{T}_R\ |$ of the bomb. Trail represents the distance the bomb falls short of its objective because of the decrease in horizontal speed after release. The decrease in speed is caused by the resistance of the air to the motion of the bomb. Now draw the vector **RL** through point L, which is determined from **PQ** and **PL**, in the direction of the heading of the aircraft and give it a magnitude $|\ \mathbf{V}_a T_f\ |$. RL represents the distance the bomb would have fallen if there had been no air resistance or wind. Now it can be seen that a bomb released at R will hit Q. Furthermore, it can be shown that for a particular wind, time of fall, and trail, any heading towards point A will result in bombs on the target if release occurs at the bomb release circle.



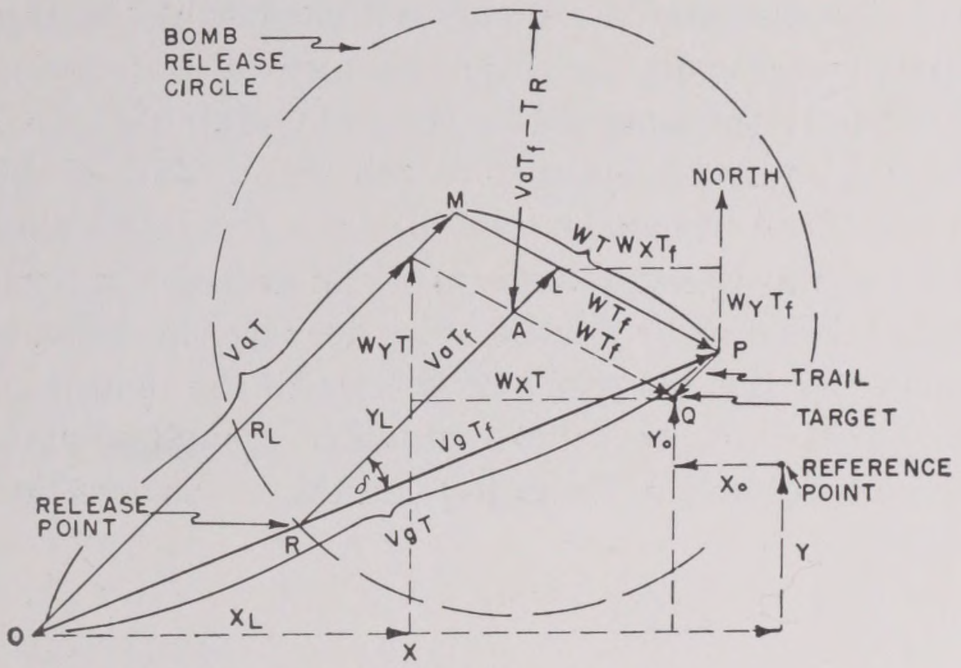
$\mathbf{T}_R$ = trail
T_f = time of fall of the bombs
Other symbols the same as for Figures 2 and 3.

Figure 4. GPI indirect bombing geometry.

It now becomes obvious that this geometry is only a special case of that discussed under course determination, providing trail is subtracted from $\mathbf{V}_a T$ and T is replaced by T_f. This being so, steering can be achieved in the same manner as previously, bombs being released when T becomes equal to T_f. It is also possible to indicate, on the time-to-go meter, the difference between T and T_f which is the time-to-go to release. Time of fall and trail are factors which are set into the computer from empirical data compiled in standard bombing tables.

The offset bombing problem is simply a variation of direct bombing as can be seen in Figure 5.

In the case of offset bombing the distance from aircraft to target can be considered as made up of two components. The first is the distance from aircraft to a radar reference point. The second is the distance from reference point to target. The distance from reference point to target is a geographical factor which can be determined from maps and entered into the computer as components, $\mathbf{X}_0$ and $\mathbf{Y}_0$. The distance from aircraft to reference is obtained as always by placing the cross hairs on the point and using the computer to determine the X and Y components of the distance. Having the components of offset and fix, the computer can add them and determine the distance from aircraft to target. Once this has been established the entire offset bombing problem becomes a direct bombing problem and is handled by the computer in the same manner as previously discussed.



Y_0 = N-S component of offset distance
X_0 = E-W component of offset distance
Other symbols same as for previous figures.

FIGURE 5. GPI offset bombing geometry.

9.2 THE GPI COMPUTER MECHANISM

In the following step-by-step discussion of the GPI computer, frequent reference will be made to Figure 6. This figure has been divided into three sections containing (A) the rate mechanisms, (B) the fix mechanisms, and (C) the course and bomb-release mechanisms. In this figure dashed lines represent mechanical linkages while solid lines are electric connections.

9.2.1 Fix Computation

Fix measurements are made with the function switch (marked *N-C-B* for navigate-course-bomb) in the navigate (*N*) position. Referring to Figure 6, part B, it is seen that the precision helipot (multi-revolution potentiometer) (1) has an a-c voltage across it supplied by transformer (2), the center tap of which is grounded. The voltage output of the helipot will vary from full voltage at one end, to zero at the center, to full voltage at the other end, as the potentiometer arm (3) sweeps across the helipot. It should also be noted that there is a phase reversal of the voltage as the potentiometer arm passes over the center of the helipot where the voltage passes through zero. The shaft of the helipot (1) has been fitted with a knob (4) and a dial (5). If a scale factor of some number of nautical miles per volt output is decided upon, the dial (5) can be given markings which indicate the helipot arm position in nautical miles. Since the helipot is linear, the dial markings will be uniform. At this point, it is observed that an adjustment of dial (5) to any number will result in the presentation of a proportional voltage X to the driver (6). The dial calibration for the computer is such that the voltage from ground to one end of the helipot represents 20 nautical miles. The driver (6) is an impedance-matching device with an input-output voltage ratio of 1/1. The input to the other driver (7) is derived in the same fashion as that described for driver (6). The voltage X_L from driver (6) represents at all times the algebraic sum of the E-W components of distance to be introduced to the Arma resolver (8). In this instance, the voltage X_L represents only the distance X shown in Figure 1. The two a-c voltages X_L and Y_L are the inputs to the Arma resolver (8).

The Arma resolver is a device used to perform vector addition of a-c voltages. It has two stator windings displaced 90 mechanical degrees from one another and two rotor windings similarly displaced. If first the two stator windings are excited by voltages X_L and Y_L respectively, and if next the rotor is turned until the voltage output of one of its coils is zero then the output of the second rotor coil will be the resultant of the two input voltages; $R_L = (X_L^2 + Y_L^2)^{\frac{1}{2}}$. Also, the position of the rotor shaft will then represent the angle whose tangent is X_L/Y_L. In practice, the shaft of resolver (8) is turned by a motor (9) under control of servo-amplifier (10) until the voltage output O of the resolver is zero. Under this condition, the other resolver output voltage R_L is equal to the square root of the sum of the squares of X_L and Y_L and represents the distance R shown in Figure 1.

The voltage R_L is applied through switches (12) and (13) to the altitude triangle solver (14). The triangle solver also has applied to it a voltage in quadrature with R_L controllable by the altitude knob (15). The potentiometer turned by knob (15) has a scale factor (miles per volt) proportional to the rest of the system, but for convenience the altitude dial (16) markings are in feet instead of miles. The output (ρ) of the triangle solver is the resultant of the voltage R_L and the altitude voltage (h) and is proportional to slant range. The voltage (ρ) enters a range mark generator (17) to produce a pip which in turn enters the mixer (18) and thence to the PPI (19) appearing finally as a range circle (20).

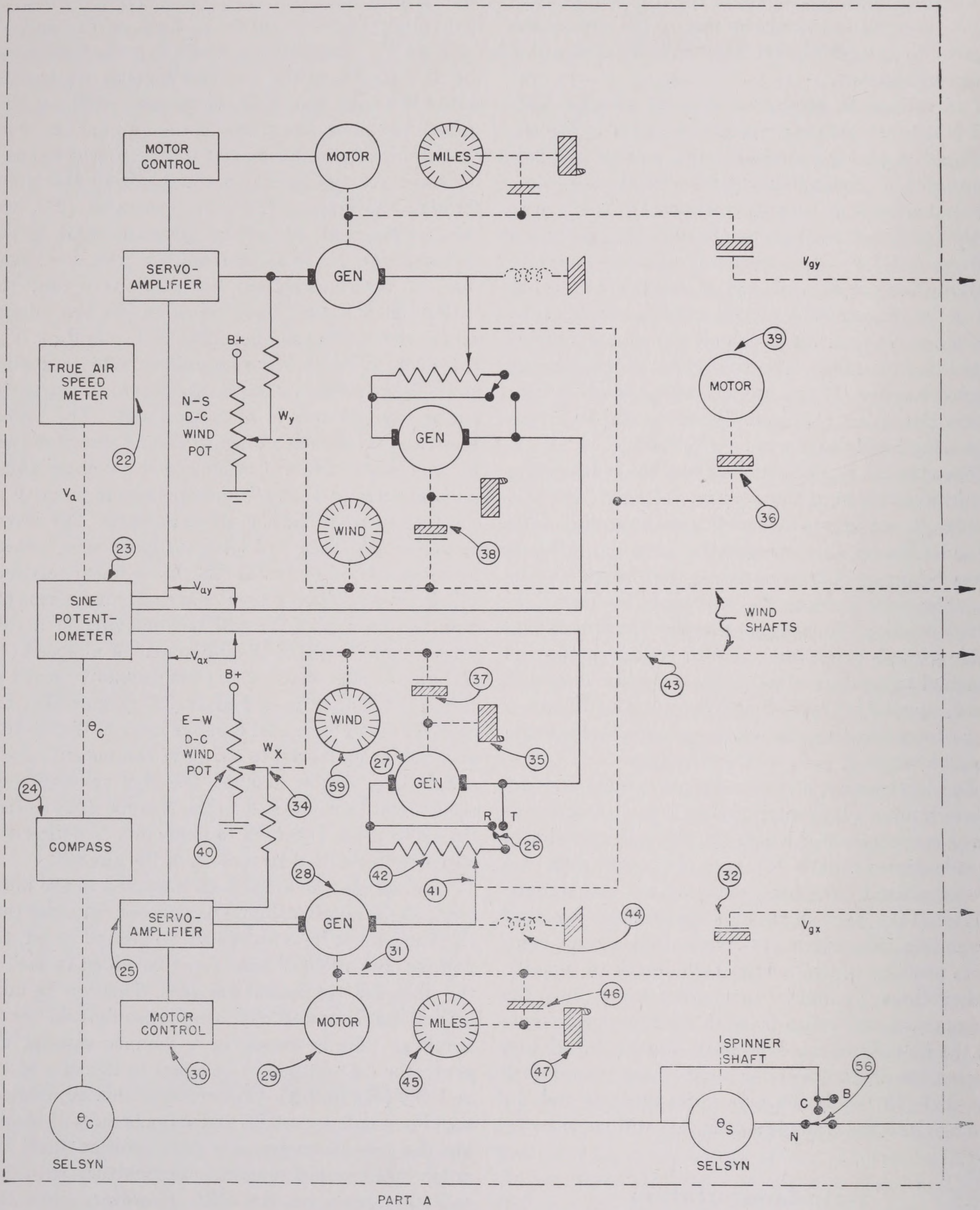
The azimuth mark portion (21) of the index comes from the addition of three selsyn voltages. The first voltage, θ_c, represents the heading of the aircraft. The second voltage, θ_s, represents the direction the antenna (scanner) points relative to the aircraft's heading. The third voltage, θ_R, represents the Arma resolver position. Since θ_s continually changes as the radar scanner turns, the azimuth mark generator is designed to produce a mark whenever the sum of θ_c and θ_s equals θ_R. This is done by causing a PPI sweep to be brightened as the scanner passes through the position where $\theta_s = \theta_R - \theta_c$ (see Figure 1).

The intersection of the range mark (20) and the azimuth mark (21) constitutes an index, the ground-range components of which are the mileages shown on the two fix dials (5) and (51), providing the proper altitude has been entered into the triangle solver (14). The altitude is determined by first grounding the switch (13), which then gives complete position control of the range mark to the altitude voltage (h), and by turning knob (15) until the range mark (20) coincides with the innermost signal on the PPI. Since this innermost signal is the ground return, the altitude knob will have been turned until the dial (16) reads the true radar altitude and the voltage into the triangle solver (14) will be correct.

9.2.2 Rate Computation

Referring to Figure 6A, it is seen that a d-c voltage, V_a, taken from the true airspeed meter (22) has been resolved into components by means of a sine potentiometer (23) which turns with the shaft of the compass (24). If the "sinepot" (23) is properly adjusted, its two voltage outputs will be $V_a \sin \theta_c$ or V_{ax}, and $V_a \cos \theta_c$ or V_{ay}, respectively, where θ_c is the heading of the aircraft. Since the two components are treated similarly, only the E-W component will be discussed here. The side of the servo-amplifier (25) connected directly to the sinepot will be considered as a reference voltage level. Continuing from this point through the sinepot (23), the generator (27), the switch (26), and the second generator (28) to the opposite side of the servo-amplifier (25), it is found that, if both generators are stationary and the switch (26) is in the "reset" position (R), the voltage across the servo-amplifier (25) is $V_a \sin \theta_c$ or V_{ax}. However, since the servo-amplifier acts to reduce any voltage across its terminals to zero, it starts the motor (29) by means of control (30). The motor speed will be of such a magnitude and direction that the generator (28) will produce a d-c voltage equal in magnitude to $V_a \sin \theta_c$ and opposite in polarity to the voltage from the sine potentiometer. The servo-amplifier (25) then will have virtually zero voltage across it and, if generator (28) has a linear relationship between voltage output and shaft revolutions per minute, the shaft (31) will be revolving at a rate proportional to the E-W component of airspeed ($V_a \sin \theta_c$). If this shaft (31) is connected by means of clutch (32) to the fix-dial shaft (33) (Figure 6B), the cross hairs can be caused to move in an E-W direction at a rate proportional to the E-W component of airspeed. In a similar manner, the N-S velocity component can be connected to the N-S fix shaft so that the radar index is caused to move in a N-S direction opposite to the N-S air motion of the aircraft.

The motion which has been imparted to the radar index so far is proportional to airspeed. In order that this movement be proportional to ground speed, the voltage equivalent of wind must be added to each of the airspeed component voltages. This can be done by moving potentiometer arm (34) so that the servo-amplifier (25) is biased in a manner causing the generator (28) output to be equal to the sum of V_{ax} and W_x (Figure 6A). Conceivably, this adjustment could be made by a trial and error process of changing the potentiometer arm (34) position until the radar index would remain in coincidence with any radar reference on the PPI. However, since this would be a tedious process, the memory-point tracking procedure was devised.


MOTOR CONTROL
MOTOR
MILES
SERVO-AMPLIFIER
GEN
V_{gy}
TRUE AIR SPEED METER
B+
N-S D-C WIND POT
W_y
GEN
MOTOR
WIND
V_a
SINE POTENT-IOMETER
V_{ay}
V_{ax}
WIND SHAFTS
θ_C
E-W D-C WIND POT
W_X
WIND
GEN
R
T
COMPASS
SERVO-AMPLIFIER
GEN
V_{gx}
MOTOR CONTROL
MOTOR
MILES
SPINNER SHAFT
C
B
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θ_C
SELSYN
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SELSYN
22
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59
PART A

Figure 6A. GPI functional diagram.

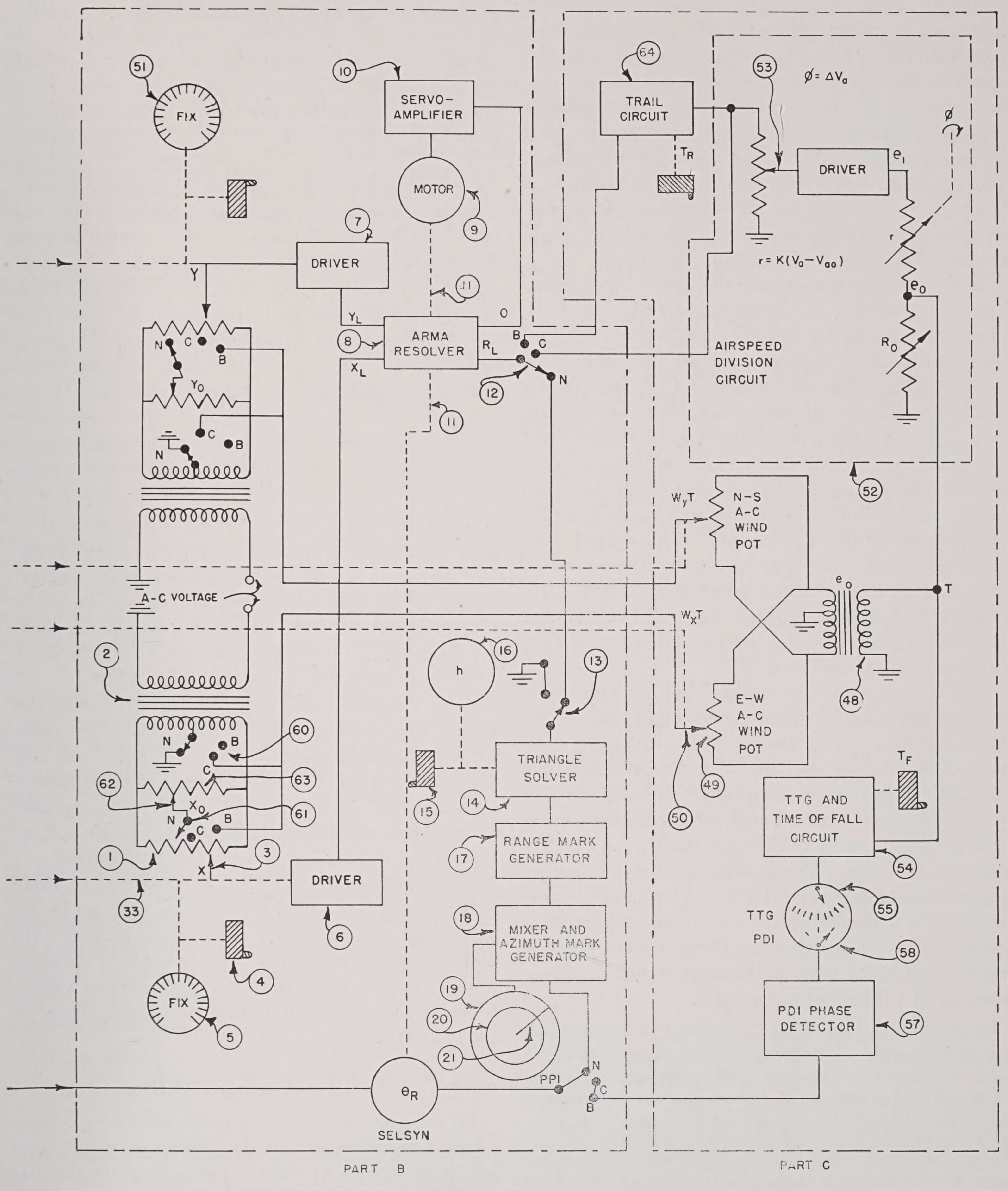

51
FIX
10
SERVO-AMPLIFIER
MOTOR
9
7
DRIVER
Y
11
Y_L
O
8
ARMA RESOLVER
X_L
R_L
B
C
N
12
11
N
C
B
Y_0
C
B
N
A-C VOLTAGE
2
N
B
60
C
63
62
X_0
N
B
C
61
1
3
X
33
DRIVER
6
4
FIX
5
64
TRAIL CIRCUIT
T_R
53
ø = ΔV_a
ø
DRIVER
e_1
r
r = K(V_a − V_a0)
e_0
R_0
AIRSPEED DIVISION CIRCUIT
52
W_yT
N-S A-C WIND POT
e_0
T
W_xT
48
E-W A-C WIND POT
49
50
h
16
13
TRIANGLE SOLVER
15
14
RANGE MARK GENERATOR
17
18
MIXER AND AZIMUTH MARK GENERATOR
19
20
21
PPI
N
C
B
θ_R
SELSYN
T_F
TTG AND TIME OF FALL CIRCUIT
54
TTG
PDI
55
58
PDI PHASE DETECTOR
57
PART B
PART C

Figure 6B, C. GPI functional diagram.

When the knob (35) is turned, generator (27) produces a voltage which is added in series with the voltage V_{ax}. This results in an increase or decrease in the speed of motor (29) for the length of time that generator (27) is in motion. This, in turn, causes the radar index to increase or decrease speed temporarily and effectively results in a small position change of the index. Since d-c voltage is proportional to velocity in this circuit, the product of d-c voltage and the time it is acting will be proportional to a distance or displacement. The control (35) is used as a vernier for displacement of the cross hairs, while the fix knob (4) is a coarse adjustment.

Now, to determine wind, the radar index must first be placed in coincidence with a fixed signal appearing on the PPI scope. This adjustment may be made with either or both of knobs (4) and (35). Secondly, the switch (26) is thrown from reset (R) to track (T) position; this also closes clutches (36), (37), and (38) and starts the constant-speed motor (39). Assuming that the effect of the E-W wind potentiometer (40) was initially that of zero wind, the cross hairs would drift away from the radar signal at a rate proportional to the X component of true wind. The constant-speed motor (39) moves the potentiometer arm (41) uniformly across potentiometer (42). Because of its constant speed, the position of the arm (41) can be considered a measure of the time (t) since the motor started.

It can be shown that, if the cross hairs are reset on the fixed radar reference at the end of time (t_1) by means of knob (35), the shaft (43) will have been turned an amount proportional to the X component of wind. This follows since, after time t_1, the displacement error caused by an incorrect rate setting will be proportional to t_1. Since the fraction of the generator voltage which is obtained by the moving potentiometer arm (41) will be proportional to time, we have a means whereby the correct relationship between the displacement and the rate correction can be determined. A more detailed discussion of this is given in the following paragraphs.

In the memory-point tracking operation, the rotation of knob (35) controls the shaft (43) and the setting of arm (34) of the d-c wind potentiometer. If the instantaneous position of this shaft is designated W_x, its rotation will then result in an output $C\,(dw_x/dt)$ from the generator (27) and $C\,(dw_x/dt)\cdot(t/T_t)$ at the potentiometer arm (41) controlled by the constant-speed motor (39). Here C is a constant, t the time elapsed since the clutching-in of the constant-speed motor (39) at the beginning of the memory-point tracking procedure, and T_t the total time necessary for the arm (41) to traverse the entire range of potentiometer (42). In the servo-loop, such an output represents a *rate* — e.g. V_{ax}.

The drift of the cross hairs from the target since the start of the procedure results in a displacement (in the X coordinate) of

$$\int_0^t \left(W_x - w_x - C\,\frac{dw_x}{dt} \cdot \frac{t}{T_t} \right) dt,$$

in which W_x is the true component of wind as distinguished from the instantaneous setting $w_x = w_x\,(t)$, and the last term of the integral represents, of course, the effect of the generator output as modified by the setting of potentiometer (42). If, now, the cross hairs are again made coincident with the target at a time $t_1 \leqq T_t$, the value of this integral becomes zero for $t = t_1$.

Accordingly, after integration of the last term by parts there results:

$$\left[\int_0^{t_1} \left(W_x - w_r + C\,\frac{w_x}{T_t} \right) dt \right] - Cw_x \,\frac{t}{T_t}\bigg|_0^{t_1} = 0. \quad (1)$$

If C is made equal to T_t, this becomes

$$W_x \cdot t_1 = w_x\,(t_1) \cdot t_1.$$

Thus the resulting value $w_x\,(t_1)$ is the true wind component, W_x, and the cross hairs should thereafter track the target automatically.[48a]

Since the rotation of shaft (43) is proportional to E-W component of wind, it is only necessary to connect it to the arm (34) of the d-c wind potentiometer, which, if properly calibrated, will cause the motor (29) to run at the E-W component of ground speed. A calibrated dial (59) may be connected to this shaft to indicate wind velocity.

Since the clutch (37) is connected only during the time a wind determination is being made, the value for wind remains constant once it is determined, and knob (35) can again be used for vernier displacement adjustments. The spring (44) is used to return arm (41) to zero, when the switch (26) is in position R, so that a new wind determination will be possible.

A *present position dial* (45) is connected to shaft (31) through a slip clutch (46). This dial can be set to read zero for any position by means of knob (47) and then will continuously indicate the E-W distance in miles to that point, since it is connected to a shaft rotating at a speed proportional to the aircraft's ground speed.

9.2.3 Course Computation

By means of a switch and some of the components already described for the determination of fix, it is relatively simple to determine the heading the aircraft should take in order that its true ground track will pass over the ground point designated on the radar scope by the cross hairs. The time which will elapse before the vehicle reaches the designated point can also be found. The means by which these quantities are obtained are described in the following paragraphs, which treat first the method of obtaining the time-to-go, T. The geometry to be solved is shown in Figure 3. The switches marked *N-C-B* in Figure 6 will be in the *C* (course) position for this portion of the discussion.

Since the computer used for course computation is of the type which solves geometric problems by means of a servo-loop, it is simplest to make an assumption regarding some point in the loop and later prove that this assumption is correct. Referring to Figure 6C, it is assumed that the a-c voltage input (T) to transformer (48) is proportional to the time required for the aircraft to proceed from point O to point P in Figure 3. The point P is the one designated by the cross hairs. The time T is obtained through the use of the circuit loop containing the transformer (48) and the airspeed division circuit (52). The output of the transformer (48) is a voltage of magnitude e_o, which will be found to be proportional to the time-to-go, T. This voltage excites the potentiometer (49) and (in the E-W channel) results in a voltage at the arm (50) which is a constant (k) times e_oW_x. Since the switches (60) and (61) are now in the *Course* position (C), this voltage is subtracted from that obtained from the potentiometer (1), which gave us a measure of the distance X (Section 9.2.1). Accordingly, the input, via driver (6), to the Arma resolver (8) is $(X - ke_oW_x)$. By combining this input with the analogous input for the N-S channel, the output of the resolver will then represent

$$[\mathbf{X} + \mathbf{Y} - ke_o(\mathbf{W}_x + \mathbf{W}_y)], \text{ or } [\mathbf{V}_gT - ke_o\mathbf{W}].$$

By the action of switch (12), which is also in position (C), the resolver output is connected to the airspeed division circuit (52). Since the function of this circuit is to divide by the airspeed, V_a, and because its output is the source of transformer voltage, e_o, we are led to the following relation for the circuit loop under consideration:

$$\frac{|\mathbf{V}_gT - ke_o\mathbf{W}|}{|\mathbf{V}_a|} = ke_o \text{ or } \left|\frac{T}{ke_o}\cdot\mathbf{V}_g - \mathbf{W}\right| = |\mathbf{V}_a|. \quad (2)$$

The inputs, $\mathbf{V}_a$, $\mathbf{V}_g$, and $\mathbf{W}$ are, however, connected by the vector relation $\mathbf{V}_g - \mathbf{W} = \mathbf{V}_a$; accordingly we are led to identify ke_o with T. For reasonable values of $\mathbf{V}_a$ and $\mathbf{W}$, that is, such that $|\mathbf{V}_a| > |\mathbf{W}|$, there is only one positive value of e_o, namely, $e_o = T/k$ which will satisfy the relation

$$|\mathbf{V}_a| = \left|\frac{T}{ke_o}\cdot\mathbf{V}_g - \mathbf{W}\right|$$

subject to the condition $\mathbf{V}_g - \mathbf{W} = \mathbf{V}_a$. In the following paragraph it will be seen how the division by airspeed is achieved, but, granting that this has been done, we see that the output of the unit (52) is a voltage which will serve as a measure of the time-to-go, T.

In the airspeed division circuit (52) the following relation holds:

$$e_o = e_1\frac{R_o}{R_o + r}, \quad (3)$$

assuming the impedance fed by e_o is large. In this equation r is equal to $K(V_a - V_{ao})$, e_o is the output voltage, and e_1 is the input voltage to the resistor network. V_{ao} is a constant which will be referred to as the lower limit of airspeed, and changes in the magnitude of r are proportional to changes in V_a. Since $r = K(V_a - V_{ao})$, equation (3) may be written as

$$e_o = e_1\frac{R_o}{R_o + KV_a - KV_{ao}}.$$

If R_o is adjusted to equal KV_{ao}, then

$$e_o = e_1\frac{KV_{ao}}{KV_a} = e_1\frac{V_{ao}}{V_a}, \quad (4)$$

and the desired variation of e_o with V_a is obtained. Suppose next the input voltage is adjusted by moving the potentiometer arm (53) until

$$ke_1 = \frac{1}{V_{ao}}\cdot R_L = \frac{V_aT}{V_{ao}}. \quad (5)$$

Then

$$ke_o = \left(\frac{V_aT}{V_{ao}}\right) \times \left(\frac{V_{ao}}{V_a}\right) = T. \quad (6)$$

This represents a voltage which, through the use of the desired proportionality constant k, serves as a measure of the time-to-go, T.

The voltage e_o which is proportional to T can be introduced to the time-to-go circuit (54) and thence to the time-to-go meter (55), which indicates the length of time before the aircraft arrives at the point indicated by the cross hairs. Likewise, since the inputs to the Arma resolver (8) are now proportional to the components of *air* range, X_L and Y_L, the shaft position of the resolver will represent the direction of vector **OM** (Figure 3), and an indication of the desired heading can be obtained. This is done by comparing the information of the compass selsyn (θ_c) and the resolver selsyn (θ_R) when switch (55) is in the course (C) position. The difference between these selsyn outputs is introduced to the phase detector (57), and thence to the PDI meter (58), which gives the direction the aircraft should turn to be on the proper heading. Figure 3 shows that this heading will be up-wind from the desired ground track by an angle equal to the drift angle (δ). Once the correct wind information has been found by the GPI, the computer will solve the course geometry automatically for all directions of approach to the point P.

9.2.4 Release and Course Computation for Bombing

The mechanism by which bomb release and course computation is achieved is very much the same as described for course computation in the preceding section. The geometry which will be discussed herein will be that for offset bombing (Figure 5). To make this discussion applicable to the direct bombing figure, simply consider the values for X_o and Y_o (offset distance) to be zero. The switch marked *N-C-B* of Figure 6 will be in the *B* (bomb) position for this portion of the discussion.

As in the previous section, the input to transformer (48) will be considered to be T, the time to proceed from present position O to future position P of the aircraft. However, here, point P will be chosen to be the position of the aircraft at the time the bombs reach the ground. As previously shown the output of potentiometer (49) is W_xT. Since the switches (60) and (61) are now in the bomb (B) position, the displacement of arm (3) of potentiometer (1), and of arm (62) of potentiometer (63) will be added algebraically to that of the arm (50) of potentiometer (49). The resultant voltage output, X_L, will be equal to $(X + X_o + W_xT)$. Since a similar procedure takes place in the N-S branch of the computer, the input to the Arma resolver (8) will again consist of X_L and Y_L. This time, however, the resolver input voltages are $X_L = X + X_o + W_xT$ and $Y_L = Y + Y_o + W_yT$. The Arma resolver (8) will act in the same fashion as previously described and the voltage output R_L will be the resultant of X_L and Y_L. Referring to Figure 5, it can be seen that the vector $\mathbf{R}_L$ is the equivalent of $(\mathbf{V}_aT - \text{Trail})$. If then the voltage R_L is taken through switch (12) to the trail circuit (64), where the voltage equivalent of the trail distance is added, the output will be V_aT. Then, as previously, the voltage V_aT is introduced into the airspeed dividing circuit (52), where it is divided by airspeed V_a, and the output voltage e_o is equivalent to time T. The calibration of the airspeed dividing circuit (52) is the same as discussed in the previous section.

The voltage e_o, which is proportional to time T, can now be introduced into the time-of-fall circuit (54), where it is compared with the known time-of-fall, T_f, of the bomb. The difference between T and T_f is then indicated on the time-to-go meter as the time-to-release-point. The voltage differential can also be used to actuate an automatic bomb-release circuit. The heading necessary to fly the ground track of Figure 5 is computed in the same manner as discussed in the part on course determination.

9.3 REQUIREMENTS WHICH THE USE OF GPI PLACES ON ASSOCIATED EQUIPMENT

In order that accurate computations can be made, it is necessary that the data used for computing be correct. How big an error can be tolerated in the data is entirely dependent upon the desired accuracy of the answer. In the case of GPI bombing it is immediately apparent that the answer should be correct to within a few feet. However, for navigation an error ten or more times larger could usually be tolerated. As a result, the requirements placed on the data-producing mechanisms associated with GPI are much more stringent for bombing than for navigation. However, since the distances and times involved on a bombing run are much less than those for navigation, the difference in requirements for the two are not nearly so great as it at first appears.

The accuracy requirements of the several components associated with GPI vary widely with the use to which GPI is to be put. In the following discussion the effects of errors in the various associated components upon the GPI will be considered.

9.3.1 Compass Requirements

The most important single factor affecting the performance of GPI is the compass accuracy. Since the

GPI integrates the aircraft's velocity continuously along components of the aircraft's heading, the velocity must be resolved correctly regardless of maneuvers of the aircraft. Similarly, the fix and steering data are resolved into components dependent upon the compass; therefore their accuracy also is a direct function of the compass accuracy.

It is possible for GPI results to be affected by any of three different types of compass errors. The first of these is a random fluctuation about the indicated heading, which occurs regardless of the aircraft's maneuvers. The second type of error is constant for a particular heading and usually results from errors in alignment, calibration, or deviation. Transient errors or temporary errors introduced by maneuvers of the aircraft are the third source.

Random errors affect the ability of GPI to navigate or bomb mainly by virtue of the vector rate errors which they introduce when a wind determination is made. In this case, the only part of the random error that matters is the change in error between the time of the first fix and the time of the second fix. The significance of these errors is illustrated by the figures shown in Table 1. In addition, random compass error at the time of the second fix will introduce a small fix error; but this is insignificant compared to the rate error.

Table 1. GPI rate errors caused by random compass errors.

Change in compass error between fixes (degrees)	Time between fixes (minutes)	Fix distance (miles)	GPI rate error (mph)
0.5	1.0	10	5.2
1.0	1.0	10	10.4
0.5	2.0	10	2.6
1.0	2.0	10	5.2

Constant errors affect the GPI in three ways; first by presenting an erroneous indication of distance traveled, second by causing an erroneous fix to be taken, and third by causing erroneous rates as a result of the fix errors introduced. The first of these is the direct result of rates being resolved into components about the wrong heading. This results in a cumulative position error. Figures for this are shown in Table 2. Fix error is caused by improper resolving of the fix components, the significance of which is illustrated in Table 3.

Table 2. GPI error in indication of distance traveled caused by constant compass errors.

Compass error (degrees)	GPI error (per cent of distance traveled)
1	1.74
2	3.49
5	8.72

Table 3. GPI fix error due to constant compass error.

Compass error (degrees)	GPI error (per cent of fix distance)
1	1.74
2	3.49
5	8.72

Even though the compass error may be constant, it is possible that its existence will introduce a vector rate error. The reason for this is that the rates are all resolved about an erroneous heading and so their direction is wrong. This will not disturb the GPI operation unless an attempt is made to refer to the earth. Then, for instance, the direction of the wind vector would be in error — in fact, the solution of the entire problem would be in a coordinate system rotated with respect to the assumed N-S, E-W axes. The error is introduced into the GPI because fixes are taken at different ranges from the radar reference. With a constant compass error this results in different fix errors. Since rate errors are a function of the difference in fix errors, a rate error will result from this constant compass error. This is illustrated in Table 4.

Table 4. GPI rate error due to constant compass error.

Compass error (degrees)	Distance of fix one (miles)	Distance of fix two (miles)	Time between fixes (minutes)	GPI rate error (mph)
1	10	7	1	3
1	10	4	2	3
2	10	7	1	6
2	10	4	2	6

The effects of transient compass errors on GPI can appear in three different ways. The first of these is an erroneous indication by GPI of distance traveled. Each time a transient error occurs the rates will be resolved about the wrong heading and position error will accumulate. The size of the GPI error will depend entirely upon the magnitude of the transient and the time for which it persists, as well as on the velocity of the aircraft. Transient errors usually arise as a result of turns made by an aircraft. Typical figures illustrating these errors are given in Table 5.

The second effect of the transient compass error

TABLE 5. Position error accumulated per turn because of transient compass errors.

Compass error (averaged over the time that the error persists) (degrees)	Time that the error persists (minutes)	Typical turning time (minutes)	Aircraft velocity (mph)	Position error (accumulated for each turn made) (miles)
1	1	0.5	180	0.05
1	2	1	180	0.10
1	1	0.5	240	0.07
1	2	1	240	0.14
5	1	0.5	180	0.25
5	2	1	180	0.50
5	1	0.5	240	0.35
5	2	1	240	0.70

is to cause fix errors. The fix error is entirely dependent upon the magnitude of the compass error and is the same as shown in Table 3.

The third effect of transient errors is to cause rate errors the same as those caused by random errors (Table 1). In this case, however, the rate errors brought about by the erroneous fixes would be larger, because changes in transient errors are usually of greater magnitude than the customary random errors. Further illustrations of these errors are given in Table 6.

TABLE 6. GPI rate errors caused by transient compass errors.

Change in compass error between fixes (degrees)	Time between fixes (minutes)	Fix distance (miles)	GPI rate error (mph)
1	1.0	10	10
5	1.0	10	52
10	1.0	10	105
1	2.0	10	5
5	2.0	10	26
10	2.0	10	52

In summary, it can be stated that fix and integration errors are the two major errors introduced directly by the compass. Rate errors in wind determination are brought in by a change in fix error regardless of the source of error, but a major part of this also comes from the compass.

At the present time, a number of compasses exist having varying degrees of accuracy, but all are somewhat faulty in construction. The Gyrosyn built by Sperry Gyroscope Company seems the most satisfactory of those investigated; furthermore it has the advantage that its basic design permits simple modifications which greatly increase its accuracy. All compasses for aircraft as of 1945 are subject to turning errors which may be of the order of several degrees.[21]

9.3.2 Airspeed Meter Requirements

GPI requires a voltage proportional to true airspeed. True airspeed, as distinguished from the commonly used indicated airspeed, is a measure of the true velocity of the aircraft relative to the air mass in which it flies. Indicated airspeed is simply an indication of the relative pressure exerted by the air mass in the direction opposite to the motion of the aircraft, and as such depends upon the density of the air which varies with altitude. A number of commercial true airspeed meters exist as of 1945 which fulfill the voltage requirement; some require slight modification.

The accuracy requirement placed upon the airspeed meter is again a matter of judgment which depends upon the bombing and navigational needs. Of course, if it is permissible to "determine wind" each time the airspeed or heading changes, almost any airspeed meter will do, since computed fictitious winds will compensate for the airspeed errors. However, if any degree of freedom of operation is desired and a correct value for wind is wanted, the airspeed requirements are very stringent.

Airspeed errors are also of three types — random, transient, and constant. The random errors do not affect GPI operation unless the magnitude of variation is extreme. Since most meters are satisfactory in this respect, random errors will not be discussed further except to say that they cause instantaneous position errors which are averaged out in the total mileage indication.

Transient airspeed errors usually occur in the form of a lag in response to changes of aircraft speed or altitude. This lag can cause either an integration error, or if it occurs during a wind determination, a rate error. Since in most airspeed meters the lag is of small magnitude and time duration and, also, since it is common for aircraft to fly for long periods at a relatively constant speed, the integration errors from this source are negligible. Moreover, if necessary, a GPI operator can avoid any error from this source in wind determination, by determining wind only when no radical changes in airspeed are being made.

The principal errors in present day airspeed meters are the constant errors. These are usually caused by faulty calibration or improper installation. The effect of a constant airspeed error is to cause the GPI to compute a wind error of equal magnitude and opposite direction. An error of this type will not cause any error in the indication of distance traveled as long as the heading on which the wind was determined is maintained. However, if a change in course is made, both an incorrect heading and rate will be indicated. As a result of the heading and the rate errors, the position indicated on the GPI dials will be in error by an amount ϵ which can be expressed as

$$\epsilon = 0.33(\delta V_a)(t_\epsilon)\left(\sin\frac{\Delta}{2}\right) \qquad (7)$$

where ϵ = position error in miles,
δV_a = constant airspeed error in mph,
Δ = angular measurement of change in heading,
t_ϵ = time in minutes elapsed since turn was made.

Table 7 gives some typical values for errors that might be expected from this source.

TABLE 7. GPI position error in miles caused by constant airspeed error.

Change of heading (degrees)	True airspeed error 1 mph	5 mph	10 mph
A. 10 minutes after the aircraft has been turned			
0	0.00	0.00	0.00
5	0.01	0.07	0.14
10	0.03	0.14	0.29
20	0.06	0.29	0.57
30	0.08	0.43	0.85
90	0.24	1.17	2.36
180	0.33	1.65	3.30
B. 30 minutes after the aircraft has been turned			
0	0.00	0.00	0.00
5	0.04	0.22	0.43
10	0.09	0.43	0.86
20	0.17	0.86	1.72
30	0.25	1.28	2.55
90	0.70	3.50	7.00
180	0.99	4.95	9.90

In general, the true airspeed information available for GPI operation is sufficiently good when compared with other data such as the compass data. However, care should be taken when an airspeed meter is installed, for even the best meter performs badly unless it receives proper pressure and temperature information. If considerable care is taken during installation and calibration, it will be found that the effect on GPI of airspeed errors will be negligible.

9.3.3 Radar Requirements

GPI requires that the radar system with which it is used provide a synchronizing pulse (trigger) as well as scanner azimuth data. The trigger is usually derived from the modulator output pulse. Azimuth data is received from a selsyn unit rotated by the radar antenna assembly. In turn (see Section 9.2.1), GPI provides an azimuth mark and a range mark as an index on the radar scope.

The previous discussion (Section 9.2.2) has shown how GPI depends upon fix information. The computation of fix determines present position relative to a reference point. Because of these two facts, anything which contributes to the accuracy of fix determination is important to the GPI performance.

The resolving power of a radar system is one factor which determines how accurately fixes can be made. Moreover, as was shown in Chapter 7, resolution depends upon the transmitted frequency, pulse duration, beamwidth, size of the PPI indicator spot, PPI sweep speed, and the persistence of the tube. As far as the present discussion is concerned, most radar systems have sufficient resolution to make extremely good navigational devices.[52a] On the other hand, the beamwidth, spot size, sweep speed, and tube persistence, which contribute to GPI fix accuracy, leave something to be desired.

Since the accuracy of GPI fix is dependent upon how well a reference signal is seen and upon the accuracy with which an index can be brought into coincidence with that signal, it is logical to examine this process. It is assumed, for the present, that the method of setting cross hairs on the radar reference is to make the azimuth mark bisect the reference and to set the trailing edge of the range mark just tangent to the leading edge of the reference. Accuracy of the range adjustment is largely dependent upon the spot size and sweep speed of the PPI tube. The accuracy of azimuth adjustment depends upon the width of the radar beam, and the range and size of the target. Both of these factors are affected by the persistence of the radar scope if the aircraft is traveling at high speed or is rolling and pitching with unstabilized antenna.

The sweep speed which should be employed on the radar set used with GPI depends once more upon the needed navigational accuracy. If the trailing edge of a range mark is considered to fall instantaneously, then the apparent point at which it falls as it appears on the PPI will be one-half the spot size of the tube beyond the true point. Likewise, if a signal rises instantaneously, it will appear to start one-half spot size ahead of its true position. Thus, if the trailing edge of a range mark and the leading edge of a signal were made tangential as they appear on a PPI, a gap would exist the size of one spot between the true edges. Since the spot size of a tube is constant regardless of sweep speed, the distance in miles that is represented in a spot size will change with sweep speed. If a signal does not rise rapidly, the previous statements are still true and, in addition, the true leading edge and trailing edge will also change as a function of radar receiver gain and PPI brilliance adjustment. Assuming a spot size of 0.5 mm, Table 8 shows the range accuracy which might be achieved if it is assumed that the gap between range mark and signal is one spot size.

TABLE 8. Range accuracy as a function of sweep speed (assuming PPI spot size is 0.5 mm).

Sweep speed (miles per inch)	Range accuracy (miles)
8	0.16
6	0.12
4	0.08
2	0.04
1	0.02

From Table 8, it is apparent that the absolute range of a target can be calibrated conveniently for only one particular sweep speed, since the spot size causes different apparent ranges on different sweeps. Also an erroneous rate of 2.4 mph would be measured if the sweep speed were changed from 4 miles per inch to 2 miles per inch during the process of measuring wind with GPI, and if the time between fixes were one minute. This would be caused by the difference in apparent range between the first and second fix of the wind measurement. For these reasons, it is recommended that one standard sweep speed be used when making range measurements. It is apparent that, if the sweep speed is to remain constant, the maximum range at which a fix can be taken will be the product of the sweep speed (in miles per inch) and the radius of PPI scope (in inches) unless special provision is made. It is suggested that the most desirable method for avoiding a limitation in range is to use a delayed sweep, preferably of the offset-center type. This permits the use of a fast sweep with low distortion at ranges much greater than otherwise.

Experimental tests performed by the authors have shown that a range mark can be adjusted repeatedly to the same point on the face of the PPI tube within ±0.01 in. using the equipment discussed here. This figure is sometimes called *setability* or *resetability*. It should be remembered that this figure for setability is necessarily true only for the method employing tangential comparison of two marks.

The technique of bisecting a radar reference with an electronic azimuth mark is somewhat more complex in analysis than is the setting of the range mark. The true size of a radar reference is the same for one range as another. Therefore, it would be expected that at great range the angle subtended by the reference would be small, and the angular accuracy with which the angle may be bisected is high compared with that of larger angles. On the other hand, if the radar beamwidth were assumed to subtend a constant angle, the width of a radar signal would be a function of the range multiplied by the angular beamwidth. This means that the farther the target, the broader its appearance on the oscilloscope and the lower the accuracy of bisecting. Actually, the width of the signal on the PPI represents target width plus the apparent radar beamwidth at the range in question. Since most antenna patterns do not achieve the ideal of constant echo signal regardless of range, the radar angular beamwidth appears to be less at great ranges than at short ranges. Accordingly, the linear width of a signal does not appear in general to increase greatly at great ranges. At close range, however, the angular width is greater. This assumes that the target echo itself remains constant in width. However, since the reflecting surfaces of various targets are different, the apparent target width may vary considerably with range.

Since the results are very much dependent upon the nature of the target, it is necessary to exercise care in selecting radar landmarks to be used for GPI fixes.[52b, c] When point targets are used as references, the azimuth resolution of the system is the determining factor for setability. The results of experimental work by the authors indicate that the setability is approximately ±0.6 degree on point targets when GPI is used with an AN/APS-15 radar. This would indicate that with an excellent target located at ten miles, the azimuth fix error would be ±0.1 mile. Thus, it is not unreasonable to expect wind-determination errors of about 6 to 10 miles per hour from this source.

In addition to the range and azimuth errors just discussed, errors which will either add to or subtract from these may be caused by the use of PPI tubes with long-persistent screens. For example, if the GPI aircraft is traveling at a ground rate of 200 mph, the edge of a signal will move a distance on the PPI corresponding to 0.16 mile during the period of one revolution of a radar scanner rotating at 20 rpm. If the persistence of the tube is great enough to preserve one picture until the next is painted, then the targets will have indistinct edges of approximately 0.1 mile in the direction of aircraft travel. Since all fix comparisons are made at the time when the radar scanner is pointed at the target in question, this particular effect of persistence only causes errors through operator confusion. However, even these errors could be eliminated by the use of rapid scan radar systems employing low-persistence PPI's.

One effect of the roll and pitch of an aircraft is a blurring of the picture caused by motion of the signal on the PPI. Unfortunately, the simple remedy of placing the cross hairs on the signal, at the time when the signal is being painted on the oscilloscope screen, is not effective in this case. This is because roll and pitch actually make the target appear at a wrong azimuth position and therefore give rise to fix error. The only effective solution to this problem (if GPI is to be used in aircraft where roll and pitch are prevalent) is to stabilize the radar antenna or the GPI cross hairs to compensate for motion of the aircraft.

9.3.4 Summary of Requirements

The GPI computers which have been designed for aircraft are capable of navigating and bombing with precision equal to and with facility exceeding that of other devices used in the past. It should be pointed out, however, that the reliability of the information supplied by a machine such as GPI can never exceed the reliability of the data used in calculating this information. With the advent of high-speed aircraft and the trend to offset bombing techniques it is entirely possible that the errors in airspeed meters, compasses and other devices which are now tolerable, may become intolerable.

9.4 GPI OPERATIONAL TECHNIQUE

9.4.1 Navigational Procedure

The practice of GPI navigation is outlined in the following four steps:

1. Determine radar altitude.
2. Measure wind.
3. Set present position (fix) dials to indicate position of aircraft.
4. Proceed with check point navigation.

1. The radar altitude is found by pushing in the altitude knob of the GPI and turning until the range mark is coincident with the innermost ground signal on the PPI scope.

2. Wind is measured and entered into the computer by first setting the GPI cross hairs on any prominent radar signal on the PPI. (The signal should be one which will not change in appearance during the next 1 to 3 minutes.) A switch button is pressed, and after a short waiting period, during which the cross hairs may drift away from the radar signal, they are reset on it. Thereafter, so long as the wind does not change, the cross hairs should remain in coincidence with any radar reference signal on which they are set.

3. The fix dials indicate, in N-S and E-W components, the ground range and direction to any reference on which the cross hairs are set. In Figure 7, the fix dials (outer dials) show that the cross hairs are set on a point which is 18 miles north and 11 miles east of the aircraft. If the aircraft should proceed to this point the zeros of the fix dials will then have moved under the cursor while the cross hairs on the PPI will have moved into the center of the oscilloscope.

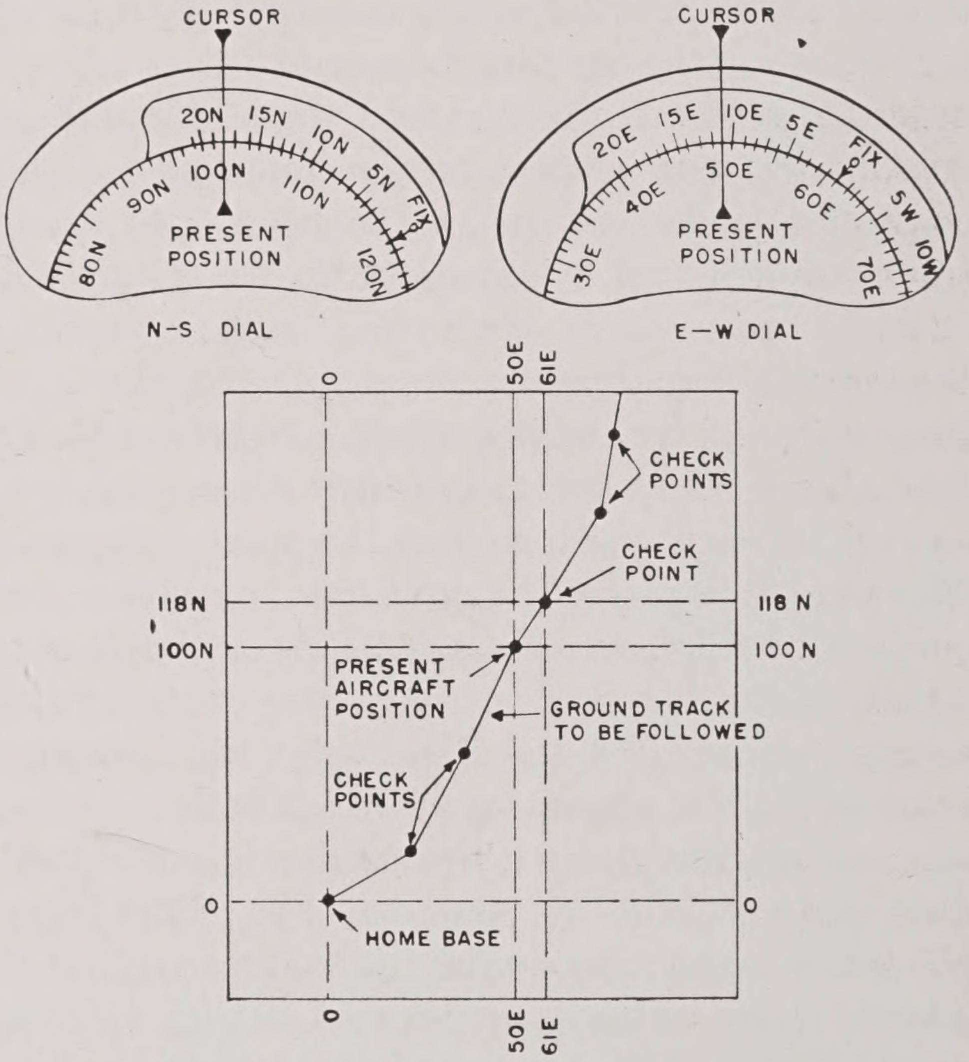


Figure 7. Procedure for check-point navigation.

The zeros of the fix dials may thus be considered as representing the PPI cross hairs. Now suppose the cross hairs to be set on a reference whose mileage coordinates are known with respect to the home base. If the present position dials are then turned until these mileage coordinates lie opposite the fix dials' zeros (cross hairs), the present position of the aircraft with respect to the home base will be indicated on the present position dials under the cursor (normally, the present position and fix dials turn together).

In the example of Figure 7, the cross hairs have been set on the PPI to a point which is known to be 118 miles north and 61 miles east of the home base. The fix dials indicate that this point is 18 miles north and 11 miles east of the aircraft. This means that the aircraft is $118 - 18 = 100$ miles north and $61 - 11 = 50$ miles east of the home base. In Figure 7 the present position dials have been set so that the coordinates of the known point (118 N and 61 E) lie opposite the zeros of the fix dials. The present position of the aircraft is now indicated under the cursor on present position dials. This constitutes step three of the navigational procedure.

4. The check-point system of navigation permits the use of the *pilot's direction indicator* [PDI] meter for indicating the heading the aircraft must follow in order to pursue a given ground track. The mileage coordinates with respect to the home base of any convenient point which lies on the desired ground track are selected by reference to an aeronautical chart or other source. This point is one over which the aircraft should pass in order to be on course (see Figure 7), and it need not reflect a radar signal. The fix dials are then turned until their zeros come opposite the mileage coordinates of the point in question. This operation places the cross hairs over this point on the PPI scope even though there may be no radar signal. If the function switch is now turned to the course position (C), the PDI meter will indicate a heading for the aircraft to fly which is upwind from the desired ground track by an amount equal to the drift angle. In addition, the *time-to-go* [TTG] meter will indicate the time in minutes before arrival at the selected point. This procedure of setting up check points for the GPI may be repeated as many times as desired until the aircraft arrives at its destination. If the aircraft has wandered off course during a time when the GPI may have been left unattended, the setting up of a single check point will bring it back to the prescribed ground track, and a second check point will cause the aircraft to be turned on course. If the check-point system is used, and if a new wind determination is made every time there is reason to believe it has changed, a predetermined course can be flown very accurately.

9.4.2 Identification of Radar Signals

Radar signals appearing on a PPI tube can be identified by use of the GPI. One procedure for this would be to place the cross hairs on the unknown signal and then to read the mileage coordinates of that signal from the present position dials opposite the zeros of the fix dials. By reference to a navigation chart showing these coordinates, the geographic location of the unknown signal can be found. Conversely, if it were desired to select a particular signal appearing among a number of other signals on the PPI, it is only necessary to set the fix dial zeros opposite the mileage coordinates of the desired signal on the present position dials. Then the cross hairs will appear over the desired signal on the PPI.

9.4.3 Classification of Reference Points for GPI

The GPI technique divides reference points into three categories:

1. Principal references are those which by nature of their shape or position relative to other signals may be easily and positively identified by the use of radar with ordinary charts. The use of GPI is not essential for these references. Principal references are used to set the present position dials at the beginning of the navigational procedure. Since GPI is subject to a cumulative position error, the present position dials may have to be reset occasionally. This should be done only when the reference can be positively identified. The importance of using only principal references to set the present position dials is stressed. The philosophy behind this is that in the absence of positive identification, the best information available is that stored in the GPI.

2. Intermediate references are those which appear as good radar signals but are not easily identified without a complete knowledge of present position. GPI use is essential for these references.

3. Local references are those which appear as small, weak radar signals. There are usually many of these unidentified signals appearing on the PPI. One of these can be picked up and identified by

manipulating the fix dials to known coordinates of the reference and allowing the cross hairs to identify it on the radar scope. The destination of the aircraft may well possess such characteristics. If the cross hairs be set to the destination signal on the radar, the GPI will compute a very accurate estimate of arrival time.

In general it should be stated that only some known discrete point of a reference should be used for fix or wind determination. The remaining larger portion of the reference signal only serves as an identification aid.

9.4.4 Bombing Procedure

Having navigated to and identified the target, there are two methods of bombing it. If it is a target which is small in size and gives a discrete radar signal, it is no doubt best to bomb by direct bombing techniques, since greater computation accuracy can be achieved in this way. However, if the target is complex or gives either a very poor radar signal or none at all, then it is better to use the offset bombing technique.

The process used for direct bombing consists of placing the cross hairs on the target desired, making sure that they are synchronized with the target, then permitting the pilot to fly by means of the PDI until bomb release point is reached. Before the bomb run, the radar-bombardier would have set the values for time of fall and trail into the computer by referring to ballistic tables. For the particular GPI described herein, there exists the disadvantage that the pilot cannot use PDI and TTG information while the bombardier is making cross hair adjustments. However, this is a fault of one particular GPI which can be removed in future designs. This limitation is not serious when the GPI is used for navigation, but becomes a definite handicap in bombing, where time is important.

The process used for offset bombing is the same as for direct bombing so far as the bombardier is concerned. However, the point used for aiming in this case is actually some radar reference other than the target. Offset bombing is used when there are no well-defined characteristics on the target which can be used as aiming points, since it permits the choice of a radar reference signal which is easily recognized and well defined. Using this reference signal and the offset technique, a more accurate determination of the position of the target can be made than is otherwise possible. This facilitates the bombing of complex or invisible targets and helps overcome the difficulty of finding suitable radar echoes which was referred to in Section 9.4.3.

9.4.5 Future GPI Techniques

The description and procedures of the preceding sections are concerned with a specific version of GPI. This GPI uses a rectangular coordinate system of computing and presenting data and has the characteristic that it works with fixes consisting of range and azimuth to a simple point. This is in contrast to other possible GPI's which might, for example, work on the basis of range measurements only to each of two beacons or other known points. Furthermore, this GPI requires the operator to judge when changes in wind make necessary a new computation of wind. There exist in the design stage several new types of GPI which are not so restricted.

Designs have also been made that permit present position to be given as degrees of latitude and longitude. Identification can also be made in latitude and longitude while the fix distance is given in miles from the aircraft to the reference. The major change that is made for a latitude-longitude presentation is multiplication of the E-W rates by the secant of the latitude in degrees.

It is desirable and rather simple to provide a system of counters and differentials in place of dials. With a system of this type there would be three sets of counters: one giving fix distance; a second giving present position of the aircraft; and the third giving the position of the cross hairs relative to the home base. The third set could be labeled identification. The counters would then be used in the same way as the dials, but their presentation would be clearer.

Other refinements of GPI methods will almost surely include continuously automatic altitude measurement. Operatorless GPI's are now (1945) being designed which solve continuously all problems of navigation, including the determination of drift angle. This type of GPI does not require a search radar but can use sonic or radar doppler principles, or beacons, to obtain continuous ground speed and drift data.

Chapter 10

BEACON BOMBING

10.1 BEACON BOMBING SYSTEMS

10.1.1 Introduction

The most precise bombing so far done with radar has involved the use of beacons (racons). There are two primary advantages in bombing on a beacon return pulse rather than on a radar echo. The first advantage is that the radar return from a target is often ill-defined because the echo signals may fluctuate considerably as the aircraft moves, or no sharp boundary of the radar reflection may exist. A beacon return comes always from the same place and has a leading edge that is clearly defined. The second advantage is that the use of a beacon eliminates the vexing problem of target identification. There is no possibility of confusion with surrounding ground echoes (clutter) and most bombing beacons are coded so that misidentification of the beacon is very unlikely.

An additional advantage of most beacon bombing schemes is that only range measurements are involved. Radar azimuth measurements, which are in general less precise than range measurements, need not be used. The ranges to two beacons are measured and this furnishes the data needed to fix the position of the aircraft in space.

Several serious disadvantages are, however, inherent in beacon blind bombing. The outstanding drawback is that the aircraft must bomb within the radar horizon distance of the cooperating microwave beacon or radar. Assuming that the ground equipment is located just inside friendly territory, an aircraft at 30,000 ft cannot penetrate further than 250 miles into enemy territory; an aircraft at 12,000 ft must bomb within 160 miles of the front line.

A second complication in beacon bombing is that the distance from the ground equipment to the target (more correctly, to the bomb release point) must be very accurately known. This calls for accurate mapping of the combat area, and in many parts of the world sufficiently good maps do not exist. The alternative is the use of the bombing system as a mapping device, flying first a reconnaissance mission and then the combat mission. In either case, the geographical location of the target must be known precisely, which calls for careful intelligence work, and the ground equipment must be accurately sited. A large amount of calculation is necessary after the geographical coordinates have been determined, in order to ascertain the desired ranges. The calculations take time, which is usually at a premium before a bombing mission. (On the other hand, the absence of target identification problems helps to reduce the necessary briefing time.)

With most beacon bombing schemes used so far, technical limitations restrict the possible approaches to the target to only a few directions. This is a disadvantage, since such operational factors as enemy flak and weather may indicate a preferred direction of approach which is not technically possible.

10.1.2 Types of Beacon Bombing Systems

Three types of beacon bombing systems will be considered as well as one type of bombing system which does not involve beacons but is in several respects similar.

H Bombing Systems

In an H system (see Figure 1) the aircraft carries either a radar or some other pulse ranging device. Two beacons are located at known points on the ground. A transmitted pulse from the aircraft trips both beacons, and the beacon replies are received in the aircraft. The range to each of the beacons is determined and the aircraft position is thus established. The airborne equipment contains devices to indicate to the pilot whether he is to the left or right of the proper course, and to indicate to the bombardier or bomb release mechanism when the aircraft reaches the bomb release point.

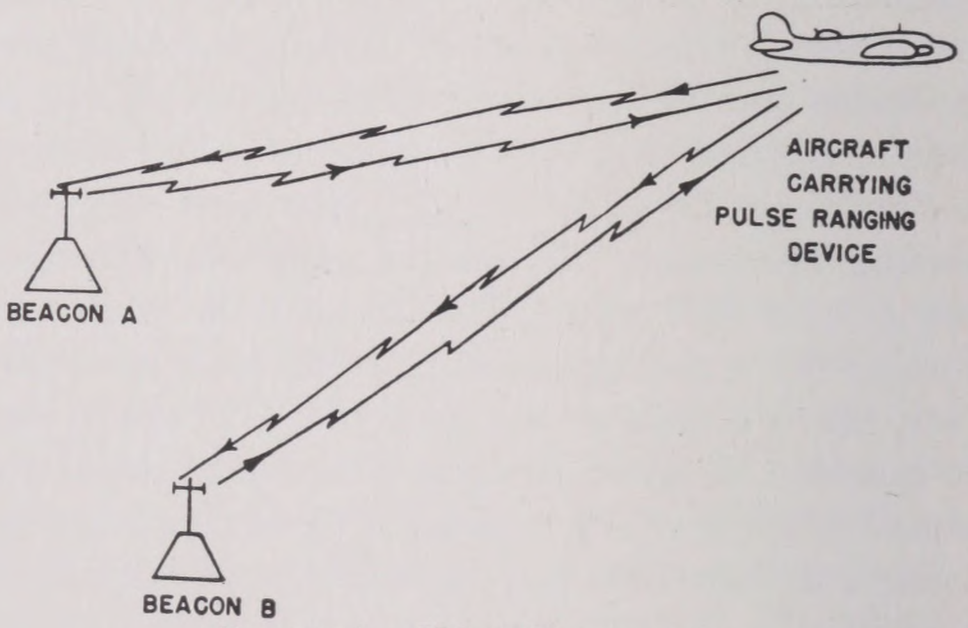


Figure 1. H bombing system.

Specific advantages of H systems as contrasted with other beacon bombing schemes are the simplicity of ground equipment and liaison requirements and the large traffic handling capacity. The simple requirements of the beacons are that they reply to every interrogating pulse and that their positions be accurately known. The operation of the ground equipment, once sited, is fully automatic, and no preparation other than normal maintenance is necessary for operational use. Since the beacons respond to every aircraft equipped with proper interrogators, the only limitation on the total number of aircraft that can be simultaneously controlled is overloading of the beacon. In general, tens to hundreds of aircraft can obtain satisfactory replies simultaneously.

The disadvantages peculiar to H systems stem from the need of precise range measurements in the aircraft. Either elaborate apparatus, or a highly skilled operator, or both, must be carried for good results. Since, in general, airborne equipment must be small, light, and rugged, it is not possible to have as accurate or as fully automatic ranging apparatus in the air as on the ground. Moreover the operator, however skilled, has to contend with the distractions of flight noise, oxygen equipment, crew duties, and enemy action.

Oboe Bombing Systems

In an Oboe beacon bombing system (see Figure 2) a beacon is carried in the aircraft and two ground radar stations make range measurements on the beacon. Here again the positions of the ground stations are accurately known, so the ranges from the two stations plus the aircraft's altitude define the aircraft's position in space. Steering and bomb release information is given to the aircraft by coding the radar interrogating pulses and incorporating suitable decoding equipment with the airborne beacon.

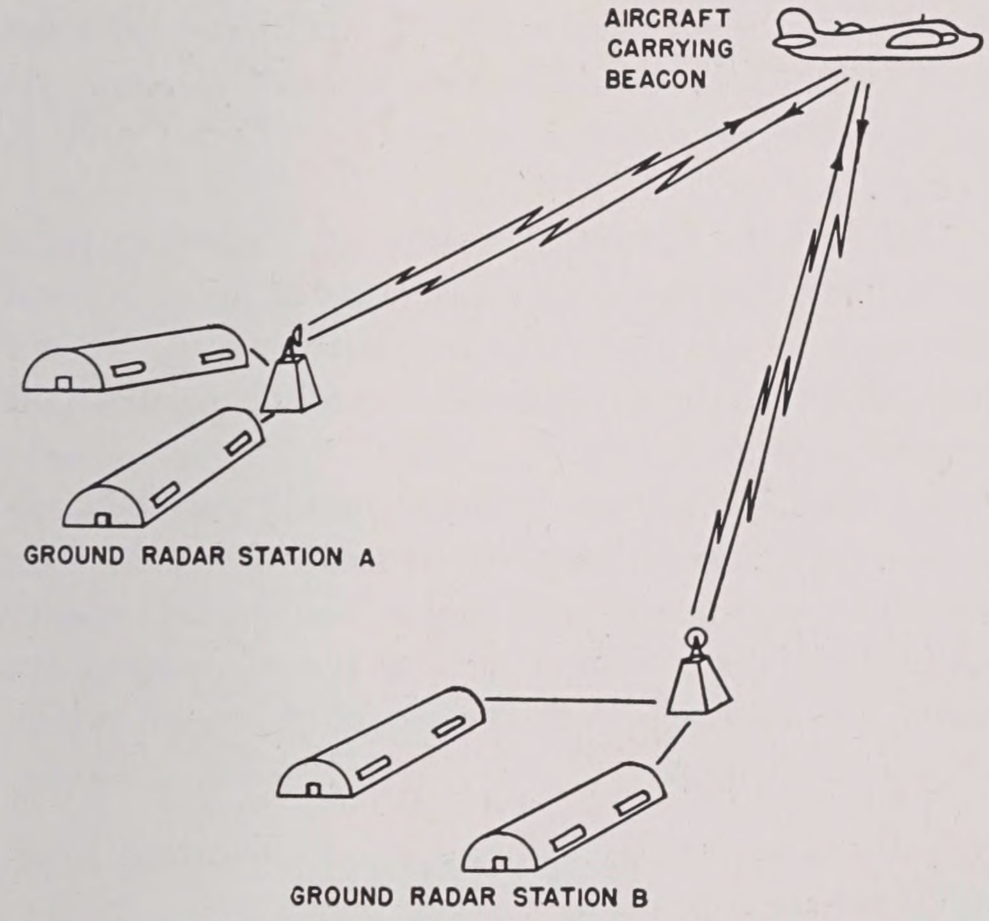


Figure 2. Oboe bombing system.

Oboe systems have the advantage that the ranging is done by skilled operators on the ground, free from combat distraction. Moreover, the ground radar set may be as large, as intricate, and as complex as desired.

The disadvantages are that a given pair of ground stations can handle only one aircraft at a time, so the only answer to the requirement for simultaneous attacks by many aircraft is the cumbersome one of building many pairs of ground stations. Furthermore, before each mission both ground stations must receive, rapidly and accurately, through secure channels, all information on the time and plan of attack and the precise ranges to the target. In practice, a complex and difficult liaison problem arises.

Beacon Offset Bombing

In this type of bombing (see Figure 3), the aircraft carries a standard bombing radar. A ground beacon, usually of the ultra-portable type, is placed at a known position in relation to the target. In the simplest form, the aircraft flies over the beacon on the beacon-target heading and releases bombs at the correct range from the beacon. In more elaborate forms, an offset bombing computer or schemes involving more than one beacon may be used.

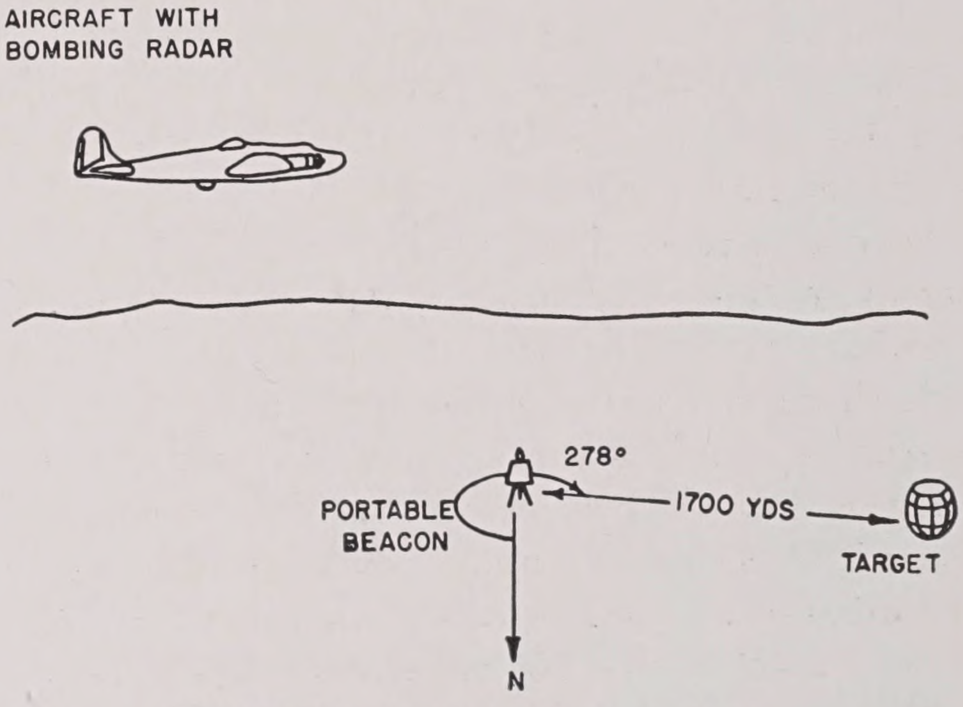


Figure 3. Beacon offset bombing.

Advantages of this system are that no airborne equipment is required other than a standard bombing radar and perhaps a stopwatch; also, the system can be set up rapidly under battle conditions. It is conceivable, for example, that a ground cooperation officer could call an aircraft flying overhead and ask that three bombs be dropped on a point 1,700 yd at 278 degrees from Marker 6.

Since it involves azimuth measurements, this beacon offset system has the disadvantage relative to other beacon bombing systems that angles must be measured. Because of this, accurate bombing can be done only within a few miles of the beacon. The flying problems involved call for considerable skill and judgment and proper coordination of the activities of the beacon crew presents an organizational problem.

Hyperbolic Navigation Systems Used for Blind Bombing

Radio navigation systems such as British Gee and American SS Loran (see Figure 4) have been used for blind bombing. These are not radar and are not beacon ranging systems, but since they are ground-based pulse systems it seems appropriate to discuss them here. The principles underlying hyperbolic navigation are discussed elsewhere.[55] Instead of ranges, time differences are measured; one time-difference reading from one synchronized pair of ground stations establishing a line of position. Two time-difference readings, from two different pairs of ground stations, give a fix by the crossing of their two position lines. The accuracy of the fix depends on the angles subtended at the aircraft by each pair of ground stations, and on the angle at which the position lines cross.

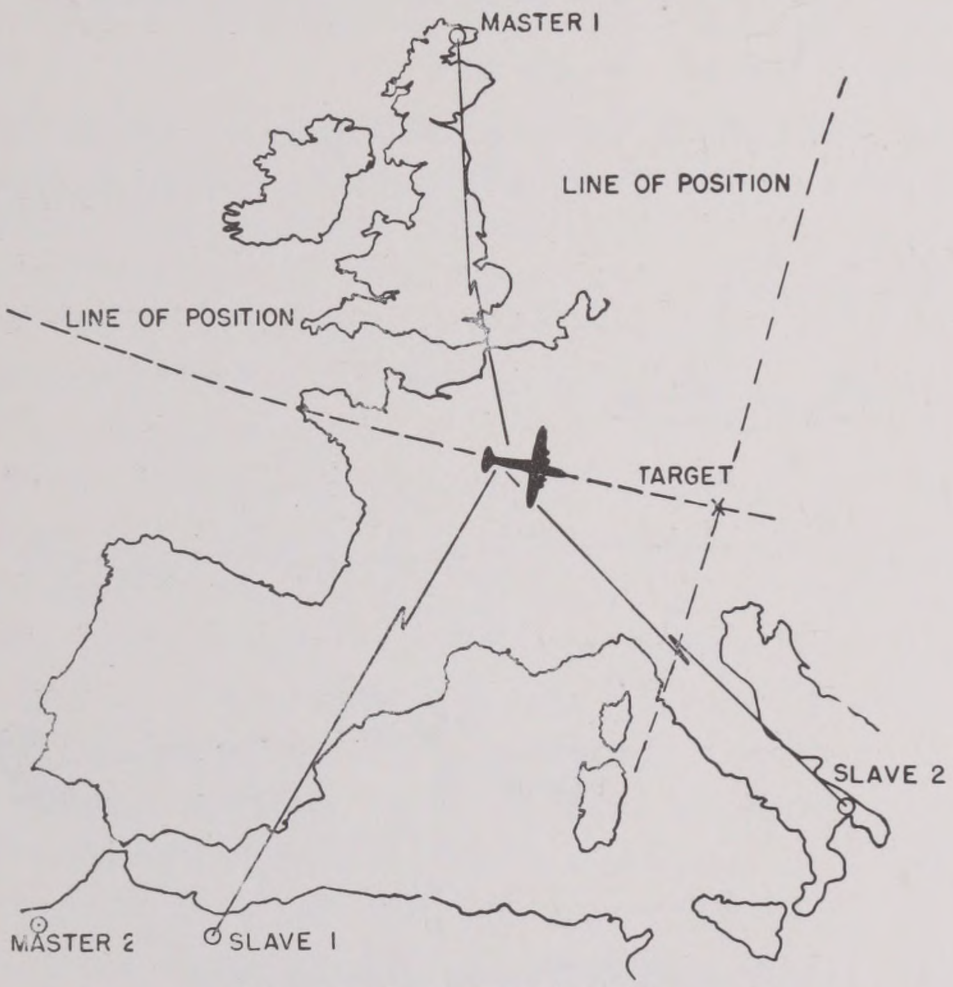


FIGURE 4. Loran bombing.

It is of interest to compare the theoretical accuracy limitations of ranging systems such as H or Oboe with those of the hyperbolic Gee and SS Loran systems. If a Gee system involving three ground stations is compared with a ranging system whose two beacons are located on the sites of the outer Gee stations, the following results will be found: first, the radial accuracy of the ranging system is always considerably superior since range is measured directly; second, the tangential accuracy is usually somewhat better for the ranging system (it is poorer near the line joining the two stations); third, the positional accuracy of the ranging systems falls off less rapidly with increasing range, being better in accuracy than the Gee system at all except the very shortest ranges.

Ordinary Loran is subject to the same limitations as Gee and has never been used for blind bombing although SS Loran has been used for bombing. With *sky-wave synchronized* [SS] Loran, the station separations are of the order of ten to fifteen times those used in Gee, and the ordinary geometrical limitations are almost entirely avoided. The four stations are located on various sides of the target area instead of at one side, and maximum accuracy is obtained near the center of this area instead of near the stations. The stations are synchronized by sky waves which are present only at night. The errors introduced by the variable time of propagation of these reflected sky waves result in average position errors of about a mile, but the service area is approximately 1,000,000 square miles. It should be noted that the same type of airborne equipment is used for Loran and SS Loran.

Gee and the ranging systems are limited in range to horizon distances, or a few tens of miles beyond, by reason of the high radio frequencies used. Even at high altitudes the coverage area rarely exceeds 75,000 square miles.

A further advantage characterizing hyperbolic systems is that no airborne transmitter is used, which simplifies equipment and makes the traffic capacity unlimited. The principal advantage of ranging systems lies in their high degree of precision within their useful range.

10.2 H BOMBING

10.2.1 General Characteristics of H Systems

A representative block diagram of an H system is shown in Figure 5. The airborne range unit generates a pulse used as the zero of the time base, which triggers the transmitter. The transmitter pulse is radiated and may or may not be coded to distinguish it from other pulses of the same frequency. This pulse is received by both beacons. The beacon reply, coded for identification purposes, is received in the aircraft and timed by the range unit which passes both beacon ranges to a computer. The computer output gives the air crew or automatic equipment the information necessary to fly the correct course and to release bombs.

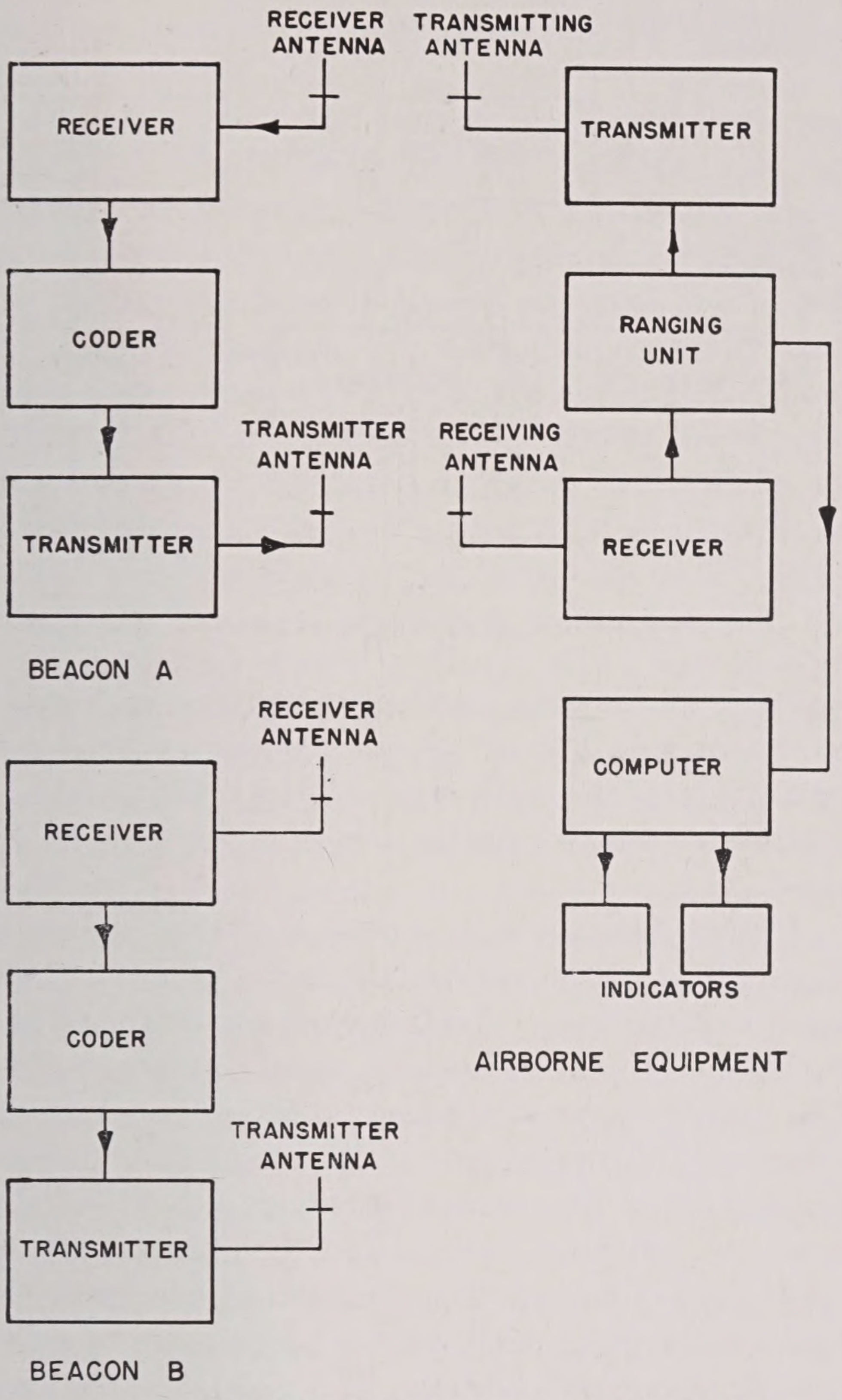


FIGURE 5. Typical H system block diagram.

BEACONS

A prime requirement for the beacons is that the delay (the time between the reception of the leading edge of the interrogating pulse and the transmitting of the leading edge of the reply) be constant. The range measured at the aircraft is the aircraft-beacon range, plus the delay in the beacon multiplied by one-half the velocity of light. The beacon delay can be measured and taken into consideration but any variation in the delay appears as a range error. Such variations in delay are caused by changes in received signal strength, duty cycle of the beacon, temperature and line voltage fluctuations, and the aging of circuit elements; and they must be minimized.[53a] Some beacons have provision for monitoring the delay and readjusting it from time to time to a predetermined value. To avoid continual tuning of the airborne receiver, the beacon frequency should remain very close to its assigned value.

The beacon receiver need not be so sensitive as the best radar receivers, since the signal it receives decreases according to the inverse square instead of inverse fourth power law (see Chapter 7). It should accommodate a somewhat broader frequency band, however, in order to receive signals from a number of radar transmitters which may spread in frequency.

AIRBORNE RANGING UNIT

For comparable absolute accuracy, the requirements on an H system range unit are more stringent than for any other radar equipment. Since ranges must be measured to within a few yards at distances of hundreds of miles, the range-unit crystal frequency should be accurate to within at least one part in one hundred thousand. Tolerances on circuit elements used to convert crystal oscillations to continuously variable time measurements must be carefully chosen to remain within the allowable limits of error. Since it is airborne, the unit must also be light, compact, and stable under varying conditions of temperature and pressure. The range unit must be capable of making measurements on two beacons, either by use of simultaneous channels, or by rapidly switching from one beacon to the other during the period of rotation of the scanner.

AIRBORNE TRANSMITTER

The transmitter requirements are those for a standard radar transmitter which should produce a pulse with a rapidly-rising leading edge.

AIRBORNE RECEIVER

As with the beacon receiver, the ultimate in sensitivity is not required, but it is necessary that the receiver preserve the shape of the radio-frequency pulse, so that time measurements made on a characteristic part of the pulse will be accurate. If both beacons reply on the same frequency, the bandwidth of the receiver should be sufficient to cover any expected frequency spread between the two, caused by the beacon transmitters drifting off tune. If the beacons reply on differing frequencies, two receivers are required, at least through the last stage of radiofrequency amplification.

Computer

The function of the computer is to transform the range data on the two beacons into information in a form useful for flying the aircraft on the bombing run and releasing the bombs. Many degrees of computer complexity exist, extending from a simple presentation that indicates to an operator when a precomputed bomb release point has been reached, to computers capable of solving the bombing triangle while flying over the target, using data corrected to that moment.

Computers have been made which take into account, in the solution of the bombing problem, some or all of the following.

1. Ground speed measured on the bombing run (by determining rate of change of beacon range).
2. Ballistics of particular type of bomb.
3. Correction for wind found on bombing run.
4. The preferred direction of approach. (Some computers allow several directions of approach; others allow an arbitrary direction of approach.)
5. Evasive action after the aircraft is committed to the bombing run.
6. Correction for curvature of a nonlinear course (since the bombs fall on a tangent to the aircraft course).
7. Changes in altitude and airspeed.

Indicators

Indicators are required to show the distance of the airplane to the right or left of the correct course, and, in more refined systems, to show whether the aircraft has the correct heading. The instant of bomb release must be indicated to the bombardier. Indicators can be dispensed with in wholly automatic systems where the output of the computer is connected both to the autopilot for actually flying the aircraft, and to the bomb release mechanism to actuate it at the correct moment. The application of this latter type of system to guided missiles and pilotless aircraft is obvious.

10.2.2 Gee-H

The most extensively used H system of World War II was Gee-H. As the name suggests, the system operates in the same frequency range and with much of the same equipment as the Gee navigational system. In fact, the equipment (A.R.I. 5525) could be used either for Gee navigation or H bombing as desired.

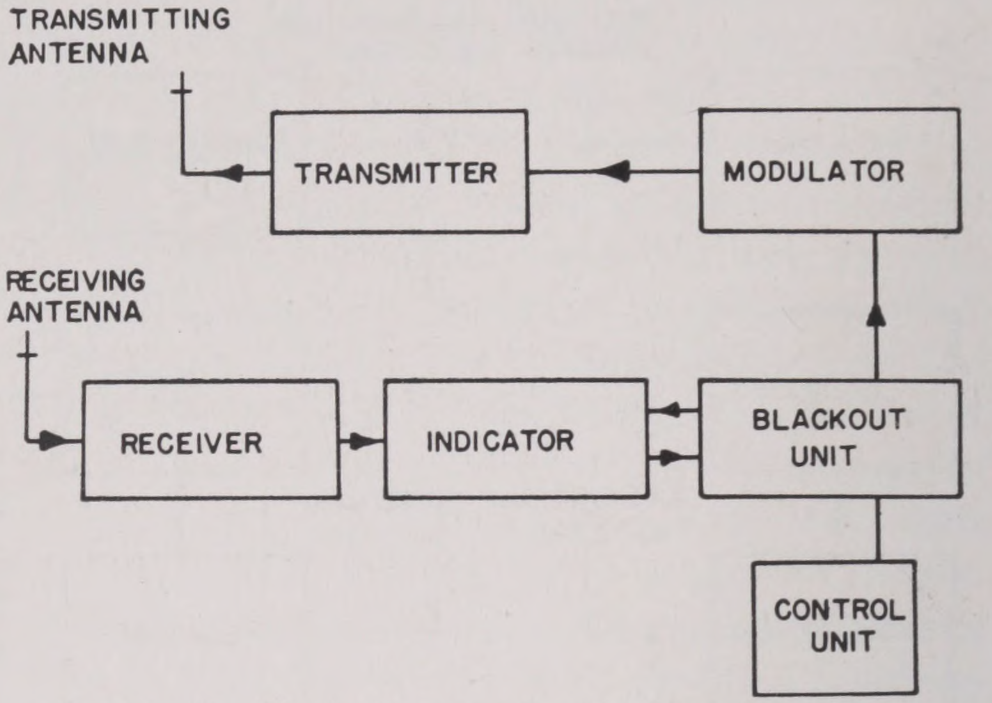


Figure 6. Block diagram Gee-H airborne system.

A block diagram of the airborne system is given in Figure 6. A crystal-controlled oscillator in the indicator is connected to dividing blocking oscillators and multivibrators to generate a trigger at the normal Gee pulse recurrence frequency of 500 c. To reduce the duty cycle of the beacons, a "blackout unit" is used which admits two successive triggers to the modulator and indicator sweeps, and then blocks out the next eight triggers. The modulator energizes the transmitter which transmits a 2-μsec pulse at a frequency somewhere between 22.5 to 30 mc. The beacons reply in the frequency range 50 to 60 mc.

The received pulses in the aircraft are displayed on either a 350-mile scale, or an expanded time base of approximately 15 miles, as desired. The two locally transmitted interrogating pulses also appear on the oscilloscope to provide the zero reference for the delay measurements. A double-trace display makes it possible to make simultaneous measurements on the two beacon return signals.

Another feature of this system is that a jitter circuit in the blackout unit desynchronizes the dividing blocking oscillator during blackout periods. If two interrogating aircraft happened to have pulses arriving at a beacon very close together (within 50 μsec or so), the beacon would reply to the first and, not having had time to recover, ignore the second. Since both aircraft operate from crystals agreeing in frequency very closely, if one such coincidence occurs, the next pair of pulses would also be close enough to interfere, and so on. To avoid this, the jitter circuit can vary the recurrence frequency slightly during the blackout period.

The airborne crystal frequency, on which the accuracy of range measurement depends, can be matched against the frequency of a carefully maintained standard crystal at the ground Gee station. Gee navigation cover is always provided in areas of H operation, and since Gee navigation is usually used in the first phases of an attack, the airborne crystal is automatically set to the accuracy of the Gee repetition frequency. The same accuracy then applies to the H ranging if the crystal trimming adjustment is not disturbed when changing from Gee to H operation.

In the initial design of Gee-H there was no airborne computer. The Gee-H operator in the aircraft observed the beacon signals on the indicator. He gave verbal instructions to the pilot to maintain the appropriate range from one beacon and to the bombardier to release bombs at the correct range from the other beacon. The bomb release point was precomputed from ballistic data, meteorological predictions, and briefed flight instructions. Later, the Royal Air Force developed a simple reversible clock computer to take account of ground speed, and the 8th Air Force developed a check point (see Section 8.3.1) method of synchronizing the Norden bombsight to calculate ground speed.

Two types of ground beacons were developed. The "heavy" beacon is a permanent installation, requiring a total maintenance and operating group of perhaps 25 people. The transmitter output was rated at peak 50 kw. A "lightweight transportable" beacon, rated at 20 peak kw, was designed in units which could be hand-carried, the entire equipment being a small truck load. A total personnel complement of fifteen was required for this type of beacon, which could also be used as a Gee ground station. Both the heavy and the light transportable beacons were continuously monitored.

One advantage of Gee-H is the extended range made possible by the relatively low frequency. Extreme ranges of 300 miles on aircraft, flying at 17,000 ft, have been reported. The alternative use of the equipment as a standard navigational aid was very useful. The ability to check and adjust the crystal frequency at will, as well as the relative simplicity of the airborne equipment, are other advantages of Gee-H. Moreover a pair of the heavy ground beacons could handle 80 aircraft simultaneously, which is more traffic than the majority of H systems can accommodate.

One major disadvantage of Gee-H results from the use of low-frequency radiation. The transmitted pulse has a time of rise of the order of a microsecond, and because the receiver video pulse must rise to some threshold value before it trips the beacon or appears on the airborne indicator, the measured range will vary with signal strength. A crude compensation for this variation can be made by increasing the video gain of the receiver for weak signals, but the beacon can make this adjustment for only one set of signals at a time, and if more than one aircraft is interrogating the beacon, some compromise must be reached. Constant monitoring of the received signal strength is needed, and, even so, ranges read at a particular aircraft may be hundreds of feet in error. A further difficulty is frequency drift in airborne transmitters so that the beacon receiver cannot be tuned correctly to all aircraft simultaneously. This fact causes further pulse distortion, and consequently delay variation.

Another disadvantage is the need for the operator to give directions to the pilot over the interphone to keep him on course, which is not easy. A further disadvantage is the crudeness of the airborne computer which at best corrects for ground speed only. Finally, the ground equipment requires a cumbersome amount of attention.

Gee-H was introduced in operations by the RAF Bomber Command in the fall of 1943, and was used extensively by that organization and RAF Second Tactical Air Force for the last eight months of the European War. In the spring of 1944 the 8th Air Force started operations with sufficient Gee-H Pathfinders to lead two of its combat wings. Bombing accuracy in training was of the order of ¼ mile, and in combat perhaps 0.8 mile circular probable error.

10.2.3 Micro-H

Micro-H is an H bombing scheme designed for use with aircraft which carry bombing radars. The prime advantage of the system is that it enables aircraft equipped with H2X (AN/APS-15, AN/APS-15A, and AN/APQ-13) radar systems to use the more precise H bombing technique within its horizon limitations. In the Mark I version of Micro-H no additional airborne equipment is required, while in the later versions only relatively minor attachments are needed.

Micro-H Mark I

The H2X radar systems were equipped for navigational purposes to receive signals from the AN/CPN-6 radar beacons. The H2X range unit, since it is used to measure range to a radar target, can make fairly precise range measurements on a single beacon. It would be possible, therefore, to do a type of H bombing by locating the beacons so that the target is equidistant from the two beacons. By flying a course such that the beacon-aircraft ranges remain equal, the bombing aircraft would pass over the target, and bombs could be dropped when both beacons were at the correct releasing range.

Such a scheme would involve the use of no additional airborne equipment or of ground equipment other than standard navigational beacons. The siting requirement would be impossibly cumbersome in practice. However, the same result can be obtained by inserting an artificial delay time in one beacon.

Suppose, for example, that beacons are sited in a combat area and it is desired to attack a target which is found to be 185.63 nautical miles from Beacon A and 147.28 miles from Beacon B (see Figure 7). Let the differences in these ranges, 38.35 miles (or 411 μsec) be inserted as an added delay in Beacon B. Beacon B then appears to the aircraft radar to be 38.35 miles further than its actual range. If the aircraft flies a course which keeps both beacons at apparently equal ranges, its course will be a branch of a hyperbola passing over the target.

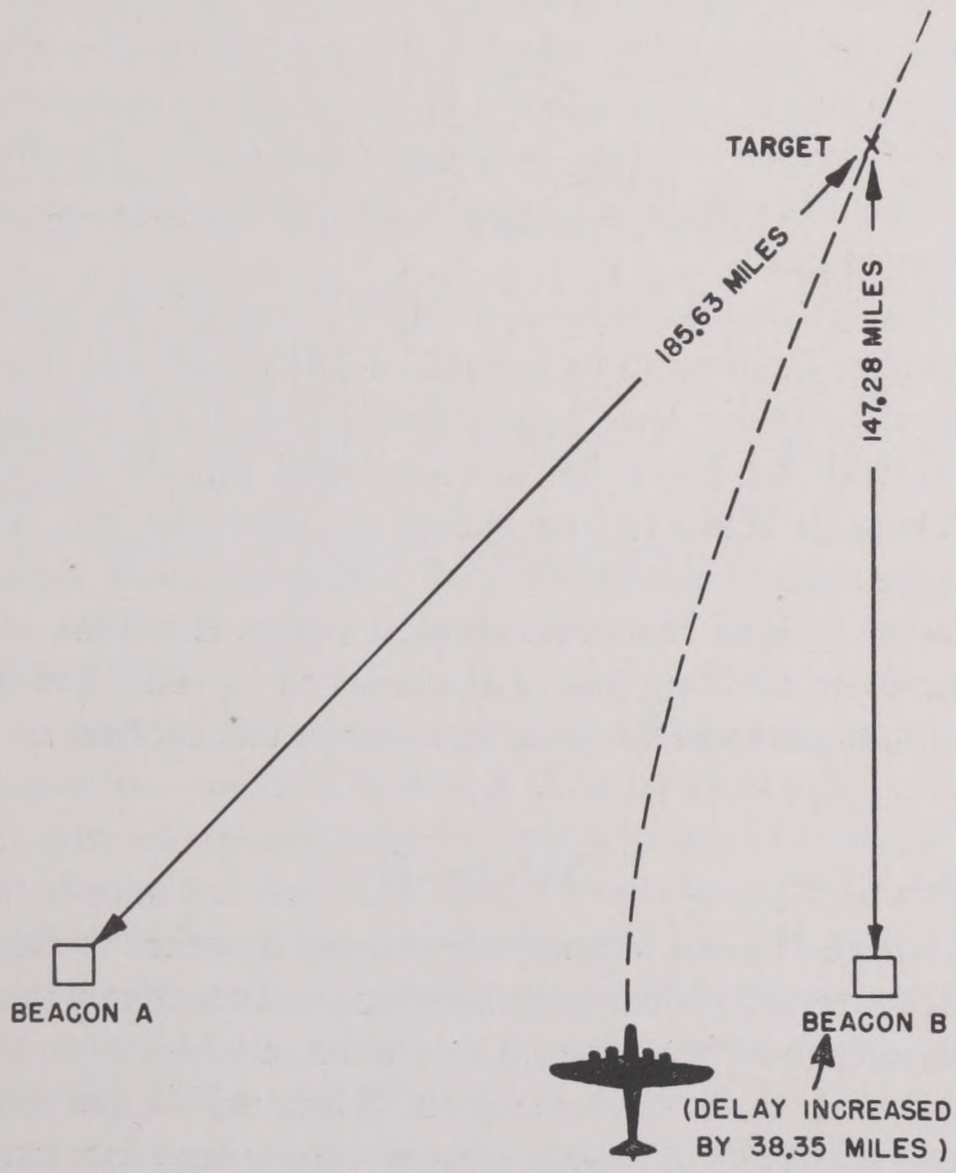


Figure 7. Delay scheme for Micro-H Mark I.

The several components of the Micro-H Mark I system are:

Beacons. Standard AN/CPN-6 beacons (or the pilot production prototype, the CXEH beacons) are modified by adding a supersonic delay line between the receiver and the coder. By varying the length of the water path through which the supersonic pulse passes, it is possible to add a delay of any value between zero and 90 miles to the beacon response, when using a delay tank that is 80 in. long.

The beacon receiver discriminates between pulses of different duration so that it responds only to pulses of width greater than 1.9 μsec, and hence does not reply to the usual one-half or one microsecond radar search pulses. The beacon reply is coded by using from two to six pulses, with long or short spacings between pulses. The number of pulses and the choice of spacings identifies the beacon. Range measurements are made on the leading edge of the first reply pulse. The beacon receiver has a pass band 110 megacycles wide, to accept all signals within the frequency band assigned to H2X. The beacon transmitter output is rated at 40 peak kw. Test equipment is built into the beacon station for monitoring frequencies, signal strength, and delay. Mobile beacon stations have been made by mounting an operating beacon and a spare beacon in a van with maintenance facilities.

Airborne Equipment. The airborne equipment is an unmodified AN/APS-15 or AN/APS-15A radar system, which will not be described here except to point out some of its limitations as Micro-H bombing equipment. Since the airborne receiver is a high gain, narrow band radar receiver, it requires frequent adjustment for optimum beacon reception (unless the system has beacon AFC such as more recently designed systems have). Some of the r-f components, since they are sharply tuned for radar echo reception on a fixed frequency rather than for beacon frequency, are apt to be 15 to 20 db below maximum sensitivity at beacon frequency.

The indicator employed is the standard H2X *plan position indicator* [PPI]. On the bombing run it is usually used with a 15-mile sweep, the target being at the extreme range of the display. A range circle of adjustable, known range is displayed on the PPI. The radar operator varies the range of this reference circle until it becomes tangent to the signal from one beacon. He then gives the pilot instructions over the interphone to fly the airplane so that the other beacon return also becomes tangent to the reference circle. He also notifies the bombardier when ranges corresponding to precomputed check points have been reached, and the bombardier uses this information to synchronize the Norden bombsight (in a manner analogous to that described in Section 8.3.1). Since the PPI range scale is 6 miles per inch, it is very difficult, although possible, to judge tangency to the reference signal (and hence to determine range) closer than 100 yd. Furthermore, experience and skill on the part of the radar operator are required to interpret an off-course indication and to give correct steering instructions for the pilot.

The radar range unit (see Section 7.3) uses a crystal-controlled oscillator with subsequent dividing stages so that any integral multiple of 10 nautical miles can be used for ranging. To this is added an additional delay, variable from zero to 10 miles, to provide the zero of the time base. A third independent delay, variable between zero and 15 miles, can be added to obtain the reference range mark on the PPI. With very careful calibration and maintenance, it is possible to determine ranges to within 50 ft in the placing of the leading edge of the reference mark.

Discussion of Micro-H Mark I. The main disadvantage of Micro-H Mark I is the substantial demand made on the skill and attention of the radar operator to keep the equipment in adjustment, to interpret the scope presentation correctly, and to direct the pilot and bombardier. Neither in combat nor in practice was the limiting accuracy of the system approached, which indicates that the instrumentation was insufficient to make full use of the available data.

A second disadvantage is that information on range to the beacons is received only once every 3 seconds, which is the period of the airborne scanner rotation. For example, an aircraft moving at 300 miles per hour moves ¼ mile between scans. On the other hand, the time required to make changes in aircraft course is about 3 sec, so more frequent information may not be useful. The 3-sec figure can be halved by the use of sector scanning.

Micro-H Mark I is not exactly a true H system because the beacon delays need to be adjusted for each particular target. This means it is necessary to have communication with the beacons before a mission, which is a serious limitation when the beacons are in forward areas. Furthermore, while many aircraft can use the beacons simultaneously, only one target can be attacked at a time.

The great advantage of Micro-H Mark I is that no additional airborne equipment is required in aircraft carrying the H2X radar and the Norden bombsight. With this combination, the aircraft has its choice of visual bombing, pure radar bombing, or H bombing, as conditions dictate. The combination gives a bombing force remarkable flexibility.

Micro-H Mark I was introduced into operations by one division of the 8th Air Force in November, 1944. It was used extensively by this division until the close of the European War. The average circular error in combat use was approximately 0.8 mile.

Micro-H Mark II

The Mark II version of Micro-H is designed to remove the limitation to a single target which characterized Mark I. This is done by adding to the standard H2X radar an airborne attachment (AN/APA-40A). (See Figure 8.) Since the angle subtended by the beacons at the aircraft is always larger than the angular width of the radar beam, the airborne radar interrogates first one and then the other beacon. It is therefore possible to switch between two sets of circuit constants in the range circuit so that the ranging is correct for one beacon when the antenna is pointed at that beacon and for the second beacon when the antenna is pointed at it. This is the principle of the AN/APA-40A attachment.

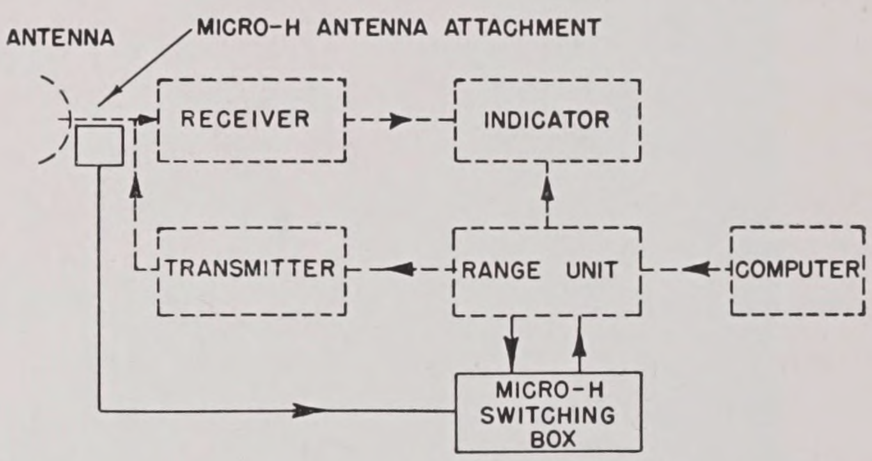


FIGURE 8. Block diagram Micro-H Mark II. Standard H2X equipment shown in dotted lines. Micro-H attachments shown in solid lines.

The range unit delays the beginning of the indicator sweep independently of the range reference mark (see Figure 9). This makes possible the addition of an apparent delay in one beacon. For example, in the case treated under Mark I, let the indicator sweep start at 135 miles when the scanner is pointed at Beacon B. When Beacon A is interrogated, let the indicator sweep start at 135 + 38.35 = 173.35 miles. If the aircraft is now flown so that both beacons appear at apparently equal range on the indicator (that is, so that the actual range minus the delay in the start of the sweep is the same for both beacons) it will follow the branch of the same hyperbola previously described in Figure 7.

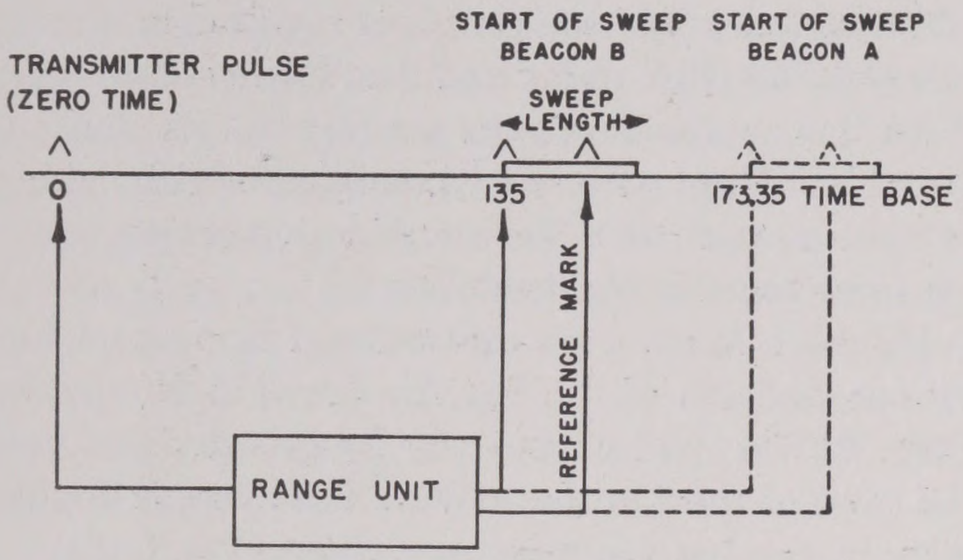


FIGURE 9. Timing diagram Micro-H Mark II.

A block diagram of the system is shown in Figure 8, while Figure 9 is a timing diagram showing the sequence of events in ranging on either beacon. From Figure 9, it is evident that, when flying a hyperbolic course, the display sweep is started at different times for the two beacons but the reference range mark occurs at the same time interval following the beginning of the sweep in each case. Figure 10 is a PPI photograph taken when an aircraft equipped with Micro-H Mark II is nearly on course and is approaching a check point.

It is also possible, with Micro-H Mark II, to fly a circular course about either beacon. In this case, a fixed reference mark is placed in the sector of the display containing one beacon, and a calibrated movable mark in the sector containing the other beacon. The course is flown so as to keep one beacon at constant range while precomputed check points determined on the other beacon are used to synchronize the Norden bombsight.

An attachment on the scanner switches the circuit elements when passing from one sector to the other. When once adjusted this automatically performs the necessary switching at the correct azimuths in each scan.

Mark II Micro-H has the advantages over Mark I that any number of targets may be simultaneously attacked, no communication with the beacon is required in setting up a mission, and circular as well as hyperbolic courses are conveniently possible. It retains the disadvantage of Mark I in demanding very high operator skill.

Micro-H Mark II was being introduced into operations by the 8th Air Force at the close of the European phase of World War II. In its few practice and combat trials, it showed substantially the same accuracy as Micro-H Mark I.

Micro-H Mark III

Micro-H Mark III was designed for use with circular courses only and is an attempt to ease the task of the radar operator in two ways: first, by switching the sweep expansion as well as the start of the sweep, the beacon at constant range can be viewed on a 4-mile scale, while the 15-mile expansion required for the determination of check points is retained in the sector containing the other beacon; second, an indication of angular deviation from course is provided, in addition to the information of displacement from course. Thus, the airborne operator can tell, for example, that his aircraft is 350 yards to right of the true course, and that the ground track of the airplane is inclined at 6 degrees to the desired ground track. He can, therefore, give the pilot instructions to get on course, and he can also calculate the correct aircraft heading that should be taken after the airplane is on course.

Heading information is obtained by making use of a feature of the AN/APA-46 (Nosmo) attachment to the H2X radar (cf Section 8.3.2). The Nosmo attachment contains provision for determining the true ground track of the aircraft by use of the pulse doppler principle. In AN/APA-46 the direction of ground track of the aircraft is displayed on the PPI by an electronic cursor. In Micro-H Mark III, the electronic cursor was placed at right angles to the ground track. In order to fly a circular course about a beacon, the ground track direction of the aircraft at any instant must be tangent to the circle and hence perpendicular to the line joining the aircraft and beacon. On the PPI display, then, the right angle cursor should pass through the beacon response. The radar operator can tell not only if the aircraft is on the correct heading, but, if not, by how many degrees the heading should be corrected.

Micro-H Mark III was not used in combat. Accuracy tests conducted by the Army Air Forces Board under simulated tactical conditions indicate a circular probable error of 200 yd.

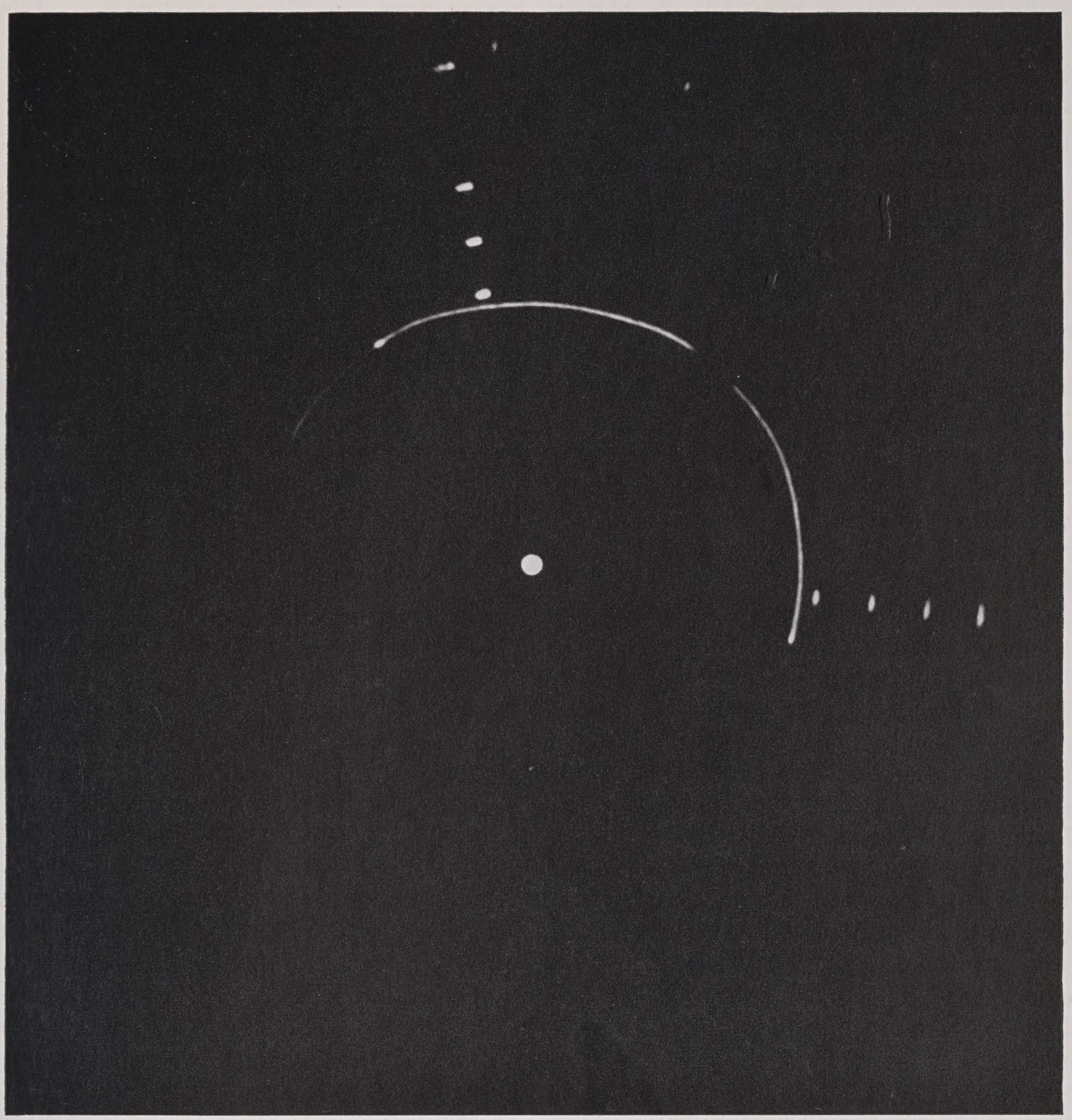


FIGURE 10. PPI photograph on a Micro-H Mark II training mission in an airplane near Nottingham, England. The aircraft is nearly on course and is approaching a check point. The beacon whose code is four evenly spaced signals is located at Beachy Head while the other beacon is at Winterton.

10.2.4 Other Applications of the H Principle

The Rebecca-Eureka beacon homing equipment has been modified for H operation, for use by RAF photo-reconnaissance aircraft. The Rebecca in its unchanged form is an airborne radar using fixed antennas and lobe switching, with a back-to-back echo matching display. The operator can tell when the aircraft is headed for the beacon by the fact that the signals are of equal strength in either lobe, and the echoes are matched in amplitude. In H operation, a single omnidirectional antenna is used, lobe switching is abandoned and the two traces can be delayed independently in 10-mile steps up to 100 miles. Circular courses are flown. To fly a circular course about one beacon at a range of 76.5 miles, and release a flash bomb at 59.3 miles from the other beacon, the operator views the first beacon on a 10-mile sweep delayed 70 miles, and the other on the opposite trace, with the same expansion, delayed 50 miles.

The system operates on any of five frequencies in the 214- to 236- megacycle-per-second band. The Eureka beacon, Mark II, weighs about 50 lb, and Mark III, about 17 lb. The beacons can readily be set up in a forward area and, once set up, can operate unattended. The British group who developed the Rebecca-H system estimate its flare-dropping accuracy as ±0.5 mile.

Two applications of the H principle have been made to paratroop dropping. Here, the problem requires that portable beacons be sited close to the front lines, for use at relatively short ranges by troop carrier aircraft flying at altitudes below 1,000 ft. A variant of Micro-H was developed, using portable 3-cm beacons (AN/UPN-3 preproduction models) and a modified AN/APS-10 radar. In principle the system is identical with Micro-H Mark II, except that the Norden bombsight is not used. Simulated tactical trials by the Army Air Forces Board indicated that paratroops could be dropped from an altitude of 500 ft with a circular probable error of 150 yd.

The same scheme was developed independently by the 9th Troop Carrier Command in Europe, using the SCR-717 airborne radar and the AN/UPN-1 portable, 10-centimeter beacons. Since the SCR-717 does not contain a ranging unit, one was developed for the purpose. It uses a pulsed crystal oscillator, the oscillations being initiated by the modulator trigger. Interpolation between 1-mile pulses is made by phase shifting the sine wave oscillations with a condenser network. Beacons could be viewed on 2- or 4-mile scope expansions, the delays in the sweeps being switched between sectors by a scanner mechanism. A synchronous tracking system was used for ranging on the beacon at variable range. In the latter sector, an air position indicator is used to move a phasing condenser so as to delay the sweep at such a rate that the beacon reply, and its reference range mark, were kept in the center of the sweep. Corrections can be made manually in the tracking rate which the air position indicator supplies. At the correct ranges, the warning light and the "jump" light are automatically lighted.

The scheme was used only in demonstrations and on practice missions. On these occasions, it gave a probable error of about 150 yd.

An interesting variation for extending the range of this device was developed by adding a *ground position indicator* [GPI]. The aircraft then flies at 1,500 ft, corresponding to an horizon range of 60 miles. An H course is flown to a point about 5 miles from the dropping zone. At the last precise H fix, the ground position indicator is started using that fix as its initial point. The aircraft then descends to 500 ft altitude, below the radar horizon, and the actual drop is made from the GPI data. The dropping accuracy of this scheme is estimated at ¼ mile, if the length of the low-altitude run is 5 miles.

10.2.5 Shoran

The best-integrated and most accurate beacon bombing system used in World War II was Shoran.[79a] However, its large-scale production came so late that its use was limited. Shoran is an H system operating in the 220 to 260 and the 290 to 320 mc bands. Almost alone of H systems, it is designed not as an attachment to or modification of some other equipment, but primarily as a beacon bombing system. In the Shoran scheme, the airborne equipment transmits on two frequencies, interrogating first one and then the other beacon. Both ground beacons reply on a third common frequency.

GROUND STATIONS

The Shoran ground stations (AN/CPN-2) are uncoded beacons, weighing about 600 lb each, complete with power supply. (Double-pulse coding has been developed, but has not seen operational use. It increases the traffic handling capacity of the system by 30 per cent.) A whole station has been flown into otherwise inaccessible territory with three or four trips of an L-5 (Piper Cub) aircraft. Recommended strength for a self-sufficient field unit complete with communications, transportation, maintenance personnel, guards, and relief is 24 men, although three men can set up the AN/CPN-2 equipment and maintain a continuous watch over it. The beacon may be set up with a nondirectional antenna or with a reflector which confines the radiation pattern to about 90 degrees. The two ground stations usually receive on frequencies separated by 20 mc, and reply on a common frequency about 75 mc from the middle frequency.

The ground stations contain provisions for monitoring and adjusting the frequency and the beacon delay time. In addition, a standard, temperature-controlled crystal, oscillating at 93,109 ± 2 cycles, produces pulses which are broadcast at intervals corresponding to exactly 100 statute miles. These pulses can be used to check the synchronization of the time base in the airborne equipment.

AIRBORNE INSTALLATION

The airborne equipment (AN/APN-3 plus comparator and K-1 Computer), weighing approximately 300 lb, consists of five units: the inverter power supply, the transmitter, indicator, computer, and comparator. Of these, only the last three need be in the Shoran operator's position. Receiving and transmitting antennas are separate, consisting of two nondirectional dipoles, less than a foot long, one on top and the other beneath the aircraft.

Indicator Unit. Ranging is done in the indicator unit. A crystal oscillator produces a sine wave at 93,109 c, manufactured with a tolerance of plus or minus 5 c and adjustable to match in frequency the ground station crystals. Divider circuits produce from this sine wave, other sine waves 1/10 and 1/100 of this frequency. Each of these three sine waves is fed into phase shifting inductance bridges, using precision goniometers. The goniometers are geared together in ratios of ten, so that a given phase shift on the 1-mile goniometer causes 1/10 that phase shift on the 10-mile goniometer and 1/100 that phase shift on the 100-mile goniometer. Crossovers (where the sine wave voltage goes through zero) or peaks from the three phase-shifted sine waves are fed to a coincidence circuit, and the coincidence generates the pulse used for timing measurements. Thus, a range of 86.937 miles corresponds to a phase shift of 313 degrees on the 100-mile goniometer; 86 × 360 degrees plus 337 degrees on the 1-mile goniometer. The goniometer bridges are temperature compensated, and the 1-mile goniometer is accurate to within 1.5 degree, or 22 ft. Separate phase-shifting networks are used for the two ground station signals. The total phase shift in each case, measured in miles, is indicated on a Veeder-Root counter having its smallest dial in the hundredths place, allowing estimates of thousandths.

From the 931-cycle oscillation, a marker pulse is generated, the timing of which may be adjusted to compensate for system delays. Then, instead of having the beacon reply fall a variable time *after* this marker pulse, the novel method is employed of varying the time when the transmitter is fired so as to make the reply coincide with the marker pulse. The marker pulse and the two beacon replies are displayed on a circular trace, radial-deflection cathode-ray tube (J scope) on a 100-mile, 10-mile, or 1-mile time base as desired. Using the fastest time base, the sweep expansion is approximately 7 in. per mile. The trace is intensified only on the sweep in which the reply occurs. One of the two beacon reply pulses is inverted, so that with correct adjustment the leading edge of one beacon reply coincides with that of the marker pulse, while the leading edge of the other beacon reply is its mirror image beneath the trace.

Computer. The Shoran system permits circular courses to be flown around either beacon. The beacon which is held at constant range is known in Shoran parlance as the "drift station" and the one having variable range as the "rate station." The Shoran computer is so designed that one sets into it the ranges from the beacons to a point over the target (corrected for several precomputed factors), the bomb ballistics, the azimuth of the aircraft ground track at release, and the angle between the ground stations, measured over the target. While the pilot is guiding the aircraft on the bombing run by means of his instruments, the operator sets in the actual aircraft heading, and adjusts the computer "rate" mechanism so the beacon reply from the rate station remains lined up with the marker pulse. The computer then automatically determines the correct course and the release point (corrected for wind and ground speed) and releases the bombs automatically.

The computer uses motor driven mechanical triangle solvers. These determine the cross-trail corrections and supply them to the indicator. An ingenious bridge circuit is used to maintain a motor driven shaft at constant but adjustable speed. This shaft drives the phase-shifting goniometer chain for the rate reply. Speed and displacement controls are used to align the rate reply with the marker pulse. Once these are correctly adjusted, the aircraft ground speed is effectively determined, and the computer multiplies ground speed by the time of bomb fall and subtracts the trail distance to determine the correct release point. Another Veedor-Root counter shows at any instant the miles to go to the release point.

Comparator. Drift station information is presented to the pilot by means of the comparator. This circuit compares the phase of the received drift pulse with that of the marker pulse, and converts the difference into a small direct current which is read on the *pilot's direction indicator* [PDI] meter thus telling the pilot whether he is to the right or left of the correct course. A differentiating circuit in the comparator shows by means of a second PDI needle whether he is increasing or decreasing his error. If both needles are centered, the pilot is at the correct range and his heading is also correct. On the more sensitive of two ranges, the pilot sees full-scale deflection for a course error of 400 ft; on the less sensitive range, full-scale deflection corresponds to a course error of 1,000 ft.

Transmitter. The airborne transmitter is conventional in design except that it may be switched rapidly between the two interrogating frequencies. The cycle of switching is of $\frac{1}{10}$ sec duration and is as follows: the transmitter broadcasts on the first frequency for $\frac{1}{30}$ sec, is silent for $\frac{1}{60}$ sec, broadcasts on the second frequency for $\frac{1}{30}$ sec, and is silent for $\frac{1}{60}$ sec. During the periods of silence, when the switching is accomplished, the transmitter is desynchronized from the time base, so that, on resumption of transmission, the timing of pulses is phased at random with respect to other airborne transmitters interrogating the same beacons. This scheme (identical in principle with the Gee-H jitter circuit, described in 10.2.2) avoids the danger of having two aircraft continuously interrogate a beacon so nearly simultaneously that the beacon can reply to only one aircraft.

Receiver. The Shoran airborne receiver has no unusual design features; it is a sensitive low-distortion superheterodyne receiver.

USE OF SHORAN

First Shoran operations were carried out in the Mediterranean Theater by the 57th Bomb Wing of the 12th Air Force in the fall of 1944. In the spring of 1945, the 42nd Bomb Wing of the 1st Tactical Air Force employed Shoran most successfully against targets in central France and southern Germany.[82a] Both the 8th and 9th Air Forces had initiated programs just before the close of the war in Europe, and at the close of the Pacific War the Far East Air Forces and the 20th Air Force had programs under way.

Typical combat bombing accuracy results are those of the 42nd Bomb Wing, where 49 per cent of the bombs dropped from 12,000 ft in March 1945 fell within 400 ft of the target. In practice, a circular probable error of 180 ft is characteristic. Tests by the Army Air Forces Board at Orlando showed a reliable ability of the operator to locate himself in space within 50 ft.

ADVANTAGES AND DISADVANTAGES OF SHORAN

The major advantage Shoran has over other radar bombing devices is its accuracy. This is not so much because it is inherently more accurate than other bombing devices as it is because it is more nearly automatic and requires less operator training, thus minimizing the human link which is responsible for the bulk of the error in most other systems. The system has the advantage that a bombardier can be trained to operate the equipment in relatively little time, since the adjustments required are comparatively simple. The pilot is required only to "fly the PDI needle." Pilot and bombardier are trained together as a team. Shoran has, in common with Gee-H and Rebecca-H, the advantage that low-drag antennas are used on the aircraft.

Shoran has the disadvantage that it is heavier and bulkier than other H systems and does not combine other features in the same equipment, such as radar bombing or long-range navigation.

10.3 OBOE BEACON BOMBING SYSTEMS

In Oboe systems, ranging is done by two ground stations. This results in two features characteristic of such systems. First, a means is provided for communicating from the ground stations to the bombing aircraft; and second, the ground radar stations may be as elaborate as desired (in practice a typical ground station has a personnel complement of 40, and the apparatus fills several rooms). Three different types of Oboe have been used, Oboe Mark I, II, and III.

10.3.1 Oboe Mark I

This system operates in the 211- to 236-mc band. In the earliest form, the airborne beacon is interrogated and replies on the same frequency. In later versions, as an antijamming measure, the ground station transmits two simultaneous pulses on different frequencies, and the airborne beacon replies on a single frequency if this coincident interrogation is received.

GROUND STATIONS

Oboe Mark I Ground Stations are high-power, directional radars, similar in transmitting and receiving equipment to the coastal early-warning radars from which they were derived. Since the ground station may be used either as a "cat" station (about which the aircraft flies at constant range) or as a "mouse" station (which gives bomb release information), two types of computers are required. In either case, the aircraft reply is displayed on each of two large A scopes. The first of these may have either a 250-mile or a 9-mile sweep, on which 1- and 10-mile calibration marks are also displayed. On the second A scope, any desired portion of the sweep may be presented together with calibration marks on a scale which can be expanded to $5\frac{1}{2}$ in. per mile.

If the station is to function as a cat, a "double strobe" is placed at the desired aircraft range (see Figure 11). This double strobe consists of two 4-μsec segments of the sweep, separated by 1 μsec. On the trace, the strobes appear as blacked-out portions. The center of the 1-μsec portion is at the correct range. The leading edge of the aircraft reply (receiver video pulse) is differentiated, and a symmetric signal is derived from this leading edge. If the aircraft is at exactly the right range, the peak of the signal comes over the 1-μsec portion, and the edges of the signal overlap the two strobes equally. If the aircraft deviates from course, the signal overlaps one strobe more than the other. Voltages are derived in the circuit which are proportional to the overlap of the signal with either strobe. These voltages are used to modulate the signal transmitted to the aircraft pilot to indicate to him whether or not he is flying the correct course. The system is sensitive enough so that 10 per cent modulation is introduced when the aircraft is 17 yd off course.

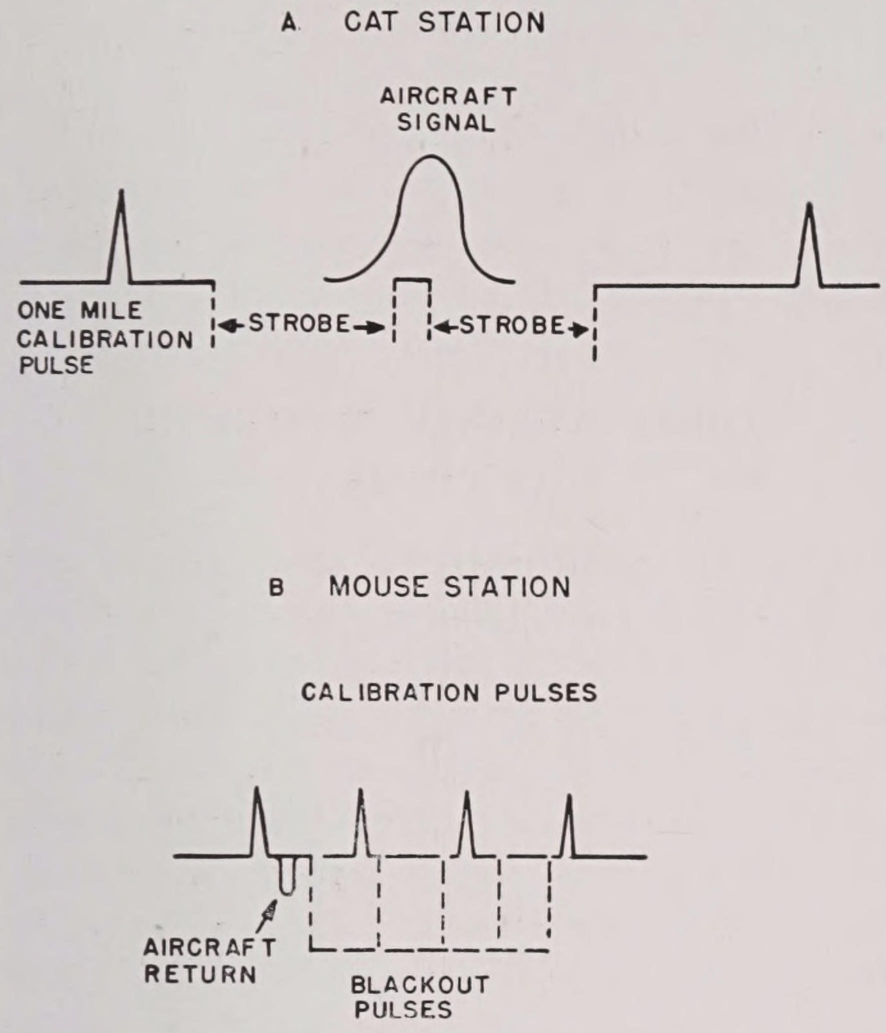


FIGURE 11. Oboe ground displays.

If the station is to operate as a mouse station, a series of equally spaced blackout pips, each being 0.5 μsec wide (see Figure 11), is so placed that the last one occurs at the release range (corrected for beacon delays and trail distance of bomb). When the airborne beacon signal reaches the first of these pips, the ground radar operator presses a button which starts a clock running. (Both mechanical and electronic timing devices have been used.) At the instant the signal reaches the middle pip, the operator presses a second button which reverses the clock. If the aircraft speed remained constant, the aircraft would just be at the corrected target range (the last blackout pip) at the instant the clock returns to zero. Actually the automatic mouse transmits a release signal at a time earlier than this by the time of bomb fall. The function of the automatic mouse, then, is to provide a warning signal and a bomb release signal, using the aircraft ground speed determined on the last portion of the bombing run.

AIRBORNE EQUIPMENT, OBOE MARK I

The airborne equipment consists of a receiver, control box, transmitter, and a filter which decodes intelligence from the ground stations (see Figure 12). This information is then presented to the pilot and bombardier by interphone. The receiver, control box, and modulator-transmitter contain no unusual features, and the filter will be described in the discussion of the communications system. The antennas are fixed, the antenna patterns being essentially nondirectional in the horizontal plane.

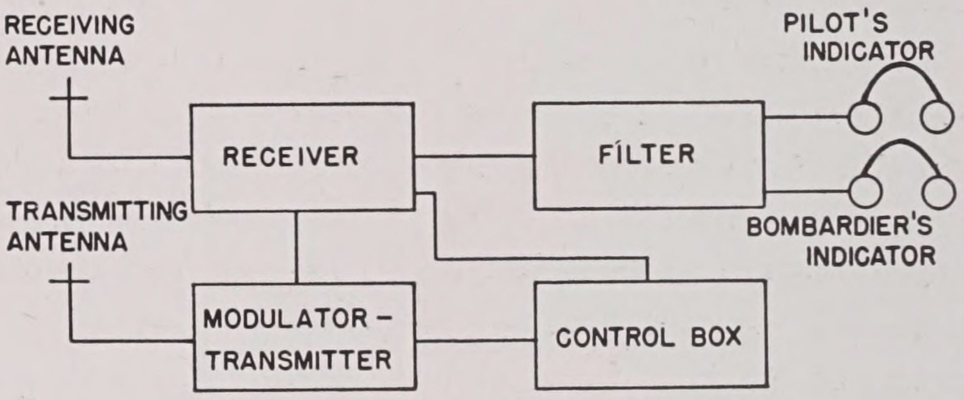


FIGURE 12. Oboe airborne equipment.

COMMUNICATIONS SYSTEM

In Oboe Mark I, a scheme for varying the time interval between successive interrogating pulses is used for communication. This scheme is known as space modulation.

The cat ground station transmits a pulse every $1/133$ second. Between each pair of these fixed pulses is transmitted a modulated pulse, the timing of which can be varied from half to three-quarters of the interval between fixed pulses (see Figure 13). In the aircraft, one output from the receiver is applied to the first grid of a peaked audio amplifier, called the filter, and resonant at 266 c. If the modulated pulse is phased at the half-way position, the filter is "rung" at its resonant frequency, and maximum output amplitude is obtained. If the pulse is phased at the three-quarters position, it is in opposition to the preceding pulse, and no filter output is obtained. In practice, the equisignal is obtained by phasing the modulated pulse at the five-eighths position, and the depth of modulation is determined by the range, centered on this position, through which the pulse moves.

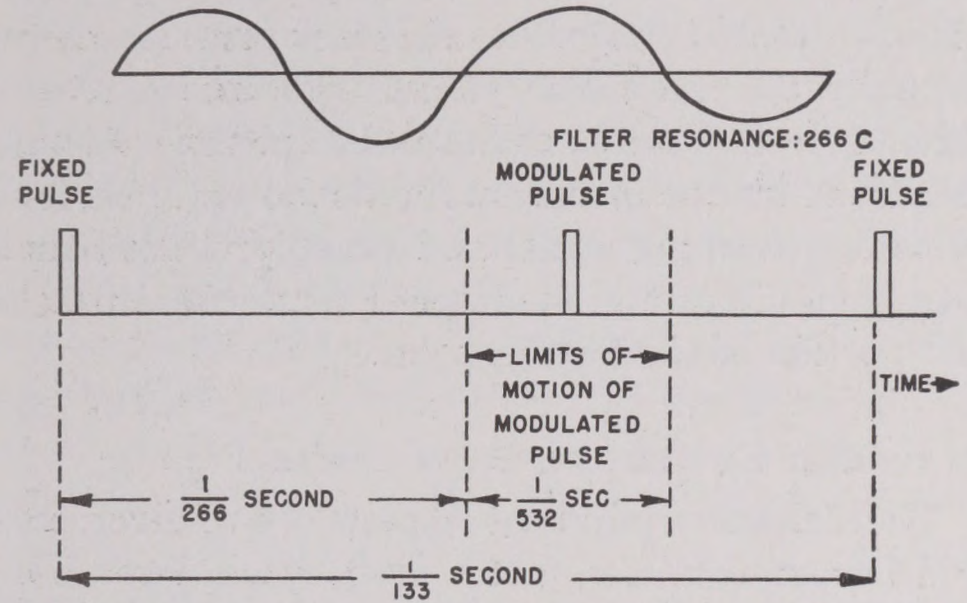


Figure 13. Space modulation communication system.

The pilot "flies a dot-dash beam"; that is, he hears a succession of dots in the earphones if he is too close to the cat station, and a succession of dashes if he is too far. As the correct range is approached, the dots and dashes merge together, and, at exactly the correct range, a steady tone is heard. This is done at the ground station by feeding the output of an unbalanced multivibrator (which produces the dots and dashes) and the output voltage from the double strobe (see "Ground Stations" in Section 10.3.1) into appropriate circuits. If the aircraft is on the far side of the course, the voltage output from these circuits is greater during the dash (long) part of the multivibrator cycle, and less during the dot part. This voltage is used to determine the delay of a phantastron which initiates the variable pulse.

Communication from the mouse ground station is provided by using a constant pulse repetition frequency of 194 pulses per second. This "rings" a second peaked audio amplifier in the airborne filter. Signals of the Morse type are sent to the bombardier by interrupting transmission, either by a hand key or by automatic keying by the "mechanical mouse" which gives the warning and release signals.

Antijamming Modifications

Two modifications of Oboe Mark I were introduced as antijamming measures. In Oboe Mark I-K the ground stations transmit simultaneous pulses on two frequencies. The aircraft carries two receivers, one for each frequency, and the receiver outputs are fed to a coincidence tube. Unless the aircraft is interrogated simultaneously on the two frequencies, the airborne beacon does not reply.

In Oboe Mark I-K with "latching," two frequencies are again used in the ground to air transmission. A delay of the order of 10 μsec is introduced between the pulses on the two frequencies. A compensating delay line is placed in the output of the appropriate airborne receiver, and the delayed signal is passed to a coincidence tube as before. The aircraft then replies only to paired pulses on the correct two frequencies if they are separated by the correct time interval.

In both the K and the K-latching systems, the airborne beacon replies on one frequency only.

Use of Oboe Mark I

Oboe Mark I, which was developed by the British Telecommunications Research Establishment, was used by the Pathfinder Force (RAF 8 Group) of the Bomber Command, Royal Air Force. The scheme was employed primarily for night flare-marking operations, in which the target was bombed with marking flares by several Oboe-equipped Mosquito aircraft, and the flares were then bombed by a main force of perhaps 500 heavy bombers. The first Oboe operation was in December 1942 and Oboe Mark I was used extensively through 1943 and with other models of Oboe to the end of the European phase of World War II. Fifty operations had been held by June 1943 and the Ruhr industrial complex was largely paralyzed by Oboe raids.

Oboe Mark I operational accuracy, when used with bombs (rather than flares) at an altitude of 30,000 feet, is about ¼ mile circular probable error.

10.3.2 Oboe Mark II

Oboe Mark II is the microwave version of Oboe Mark I. The transmitting and receiving equipment is in the 3,150 to 3,240 mc band, while the ranging and communications systems are unchanged in principle.

Ground Stations

Several types of Oboe Mark II ground stations were developed. In the fixed (permanently installed) ground stations, the equipment is located in buildings. Modified ASG 10-cm transmitters and modulators were used, delivering 30 kw pulse power into

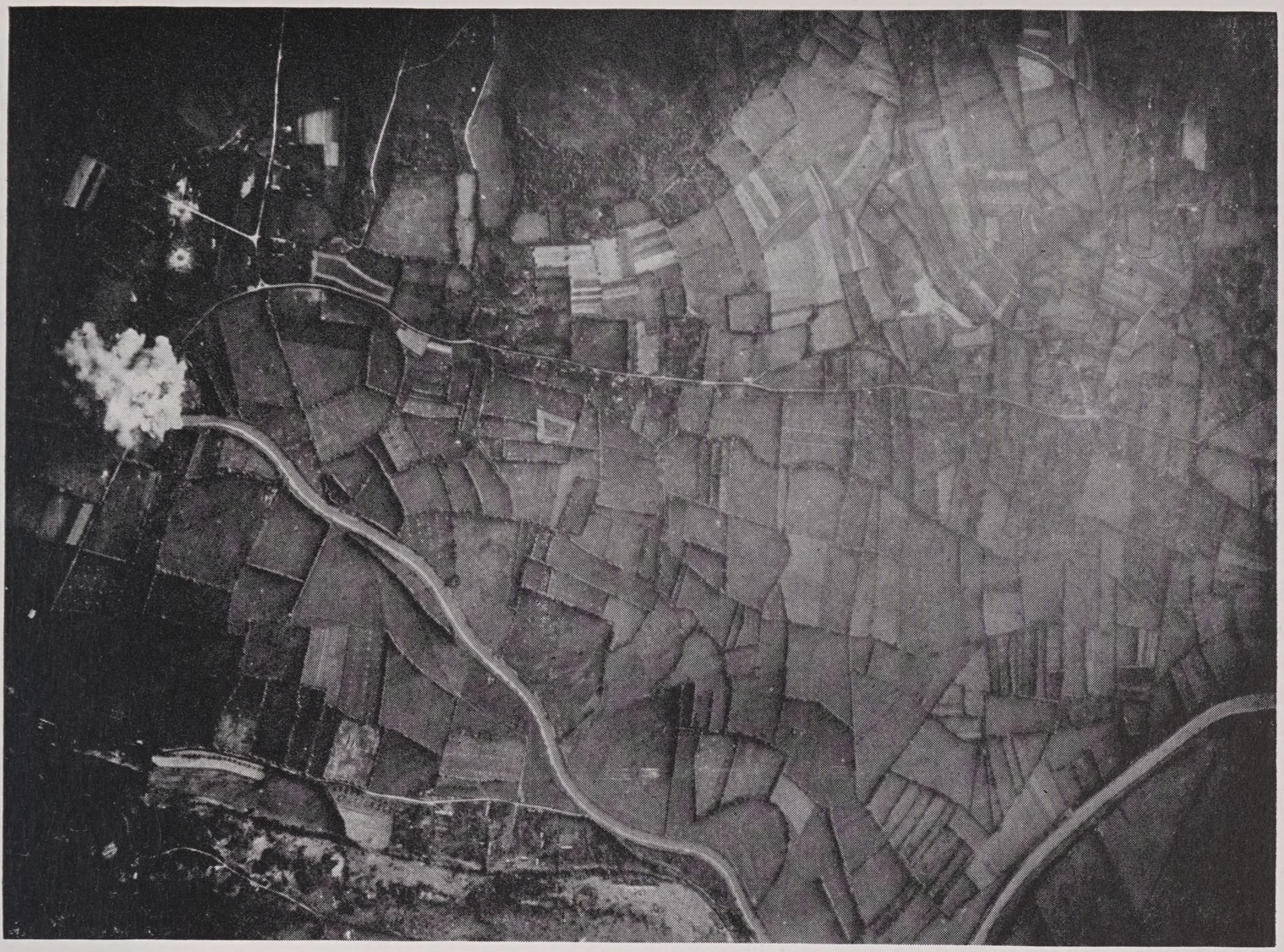


FIGURE 14. Bomb strike photograph showing the destruction of a bridge in Northern France by airplane equipped with Oboe Mark II. (U. S. Army.)

highly directional parabolic reflectors. Tunable magnetrons were installed and the transmitting frequency was constantly monitored to insure transmission on the assigned frequency.

In the mobile ground stations, the same equipment is mounted in two vans. A third van carries power equipment, and the three vans with associated vehicles make up a convoy which can be moved into a site and put into operation as soon as the necessary communications links are established.

OBOE MARK II EQUIPMENT

The airborne equipment for Oboe Mark II consists of a modified ASG airborne radar transmitter-modulator, a receiver of British manufacture, and the same type of filter as used in Oboe Mark I.

The antenna is a vertical dipole array, giving a beamwidth of 15 degrees in the vertical plane and 60 degrees in the horizontal plane. The antenna can be rotated to the correct bearing to receive the ground station.

USE OF OBOE MARK II

Oboe Mark II was developed jointly by the British Telecommunications Research Establishment and the Radiation Laboratory. It was felt that the conversion to 10-cm frequencies made the system substantially more secure than Mark I. Oboe Mark II was used by 8 Group (Pathfinders) of the Bomber Command, Royal Air Force from February 1944, to the close of the war. The 9th Bomber Command, USAAF, also equipped one Pathfinder Squadron with Oboe Mark II. The American group had its first Oboe operation in March 1944, and used the system extensively from that time to the end of the European phase of World War II.

Typical combat accuracy figures are those for the 9th Bomber Command in June and July 1944, giving a circular probable error of 700 ft. Figure 14 is a strike photograph taken from an airplane flying under Oboe Mark II control. For practice bombing, the circular probable error is about 450 ft.

10.3.3 Oboe Mark III

Oboe Mark III is an attempt to increase Oboe traffic handling capacity without increasing the number of radio frequency channels. This is done by using several different pulse recurrence frequencies, each furnishing one communication link, on the same radio frequency. As originally conceived, each ground station would have one transmitter and one receiver, and would have separate displays and computing equipment for each aircraft controlled. One ground station transmitter would then control several aircraft simultaneously. As used operationally, the spread in airborne frequencies was such that it was considered better to have one ground station transmitter and receiver, as well as displays, and computers, for each communication link desired, but several ground stations could operate simultaneously on the same radio frequency. Oboe Mark III operates on the same radio frequency (in the 10-cm band) as Oboe Mark II, and the transmitting and receiving equipment is identical in the two systems.

COMMUNICATIONS SYSTEM

In Oboe Mark III, each ground radar station is assigned a characteristic pulse recurrence frequency (97.5 pulses per second is a representative value) and no movable pulses are used. Intelligence is conveyed by modulating the duration of the interrogating pulse between 2 and 4 μsec. Thus, a succession of 2-μsec pulses produces no audio tone in the filter output and a succession of 4-μsec pulses produces maximum audio output. A dot-dash modulation is obtained by using a voltage (produced in the same manner as the voltage which phases the movable pulse in Mark I and II) to vary the duration of the pulse between these limits, the "equisignal" being a succession of 3-μsec pulses.

AIRBORNE EQUIPMENT

The airborne equipment differs from that of Oboe Mark II only in the use of a new type of filter. This filter must accept only pulses which occur at the correct pulse repetition frequency and must demodulate these pulses to provide audio signals for the pilot and bombardier.

Selection of the correct frequency is accomplished by use of a phantastron (delay circuit) chain. In the example given above of 97.5 pulses per second, the interval between pulses is 10,257 μsec. Two phantastrons in series (so that each phantastron recovers during the half cycle when the other is running) produce a blanking pulse which deadens the receiver for 10,205 μsec. The end of this pulse starts another phantastron which runs for 300 μsec or until a signal appears from the receiver, whichever occurs first. While the latter phantastron is running, the receiver is sensitive. The end of the pulse from this phantastron starts the first phantastron again, so that in the absence of a signal the phantastron cycle is completely free-running.

If a signal occurs within the period of sensitivity of the receiver, this signal is accepted. Accepting the signal starts the blanking phantastrons, and the receiver is not again sensitive until about 50 μsec before the next signal from the same ground station is expected. When that signal arrives, the process is repeated, so the filter "locks on" to the ground station transmission, accepting all pulses. If, however, the signal initially occurs during the "dead time" of the receiver, the sensitive time of the receiver is increased 250 μsec per cycle, and within ½ sec the filter cycle will have advanced in phase sufficiently to accept a signal and thus "lock on" to the ground station transmission. It is thus possible to accept a ground station transmitting at 97.5 pulses per sec, and reject one transmitting at 99 pulses per sec.

The filter removes the first 2 μsec width from the accepted pulses and derives a d-c voltage which is proportional to the remaining duration of the pulse. This voltage determines the gain of an audio amplifier which amplifies a constant audio frequency signal, and the amplifier output is supplied to earphones. Separate channels in the filter are used for the cat and mouse stations, the audio outputs going to the pilot and bombardier respectively.

USE OF OBOE MARK III

Oboe Mark III first saw operational use in the summer of 1944, and was gradually replacing Oboe Mark II at the close of the European bombing operations. In addition to increasing the traffic handling capacity of the centimeter Oboe system, the Oboe Mark III is more secure than Oboe Mark II, because jamming pulses, to be effective, must not only be on the correct radio frequency but also on the correct pulse recurrence frequency. Oboe Mark III was used by the RAF and by the 9th Bomber Command.

Accuracy of the Oboe Mark III system, as would be expected, is the same as that of Oboe Mark II.

10.4 BEACON OFFSET BOMBING

10.4.1 Beacon Offset Bombing Technique

In beacon offset bombing, portable beacons are placed near the target as reference points for offset bombing by radar equipped aircraft. Techniques have been developed for the use of this scheme at low (100 to 500 ft) and medium (8,000 to 12,000 ft) altitudes. The usual procedure is to fly over the beacon on the beacon-to-target ground track and release bombs at a time after passing the beacon such that the bombs strike at the target distance from the beacon.

Several equipment combinations are possible. In the 160 to 234 mc range, the following may be used:

1. Rebecca (AN/APN-12 or AN/APN-5) as airborne equipment with Eureka beacons (AN/PPN-1, AN/PPN-2, and AN/TPN-1).
2. SCR-729 airborne systems with modified SCR-695 beacons.
3. SCR-540 airborne systems with modified SCR 695 beacons.

In the microwave region (3,000 to 10,000 mc), the following combinations can be used:

4. BUPS (AN/UPN-1 or AN/UPN-2) beacons with SCR-717, SCR-720, or AN/APS-2 airborne radar systems.
5. BUPX (AN/UPN-3 and AN/UPN-4) beacons with AN/APQ-13, AN/APS-15, AN/APS-15A, AN/APS-10, or AN/APS-4 radar systems.

10.4.2 Low Frequency Systems

Rebecca is an airborne interrogator-receiver, using fixed antennas on either side of the aircraft, and an echo matching presentation to determine when the beacon is dead ahead. Rebecca transmits on any one of five preselected radio frequencies in the 214 to 234 mc band, and receives on two preselected and adjacent radio frequency channels. Eureka is an ultraportable transponder beacon with five receiver and five transmitter channels chosen to work with Rebecca. The other combinations work together as do Rebecca-Eureka. The SCR-729, for example, operates in the 157 to 186 mc band and the SCR-695 (an airborne beacon in its unmodified form) acts as the ground beacon.

Advantages of Low-Frequency Systems

The ground beacon is highly portable. The Eureka beacon complete with battery and mast weighs 32 lb, and can conveniently be carried by paratroopers when jumping. (Comparable microwave beacons are twice as heavy.) Because of greater low-frequency diffraction around obstacles, siting restrictions are less severe than for microwave beacons. A Eureka beacon set up below tree level in wooded territory can be seen by a Rebecca (altitude 8,000 ft) at 28 miles. Comparable microwave performance in such terrain yields ranges of 6 to 15 miles.

One man can set up a Eureka and put it in operation in 60 seconds.

Disadvantages of Low-Frequency Systems

The primary argument against low-frequency systems is the poor azimuth discrimination when compared with the microwave systems. If the ground range from the beacon to the aircraft is much less than the aircraft altitude, satisfactory azimuth indication cannot be obtained. Eurekas on a given frequency cannot be placed closer to each other than 3 or 4 miles even for low-altitude bombing, if they are to be resolved in azimuth. The siting of a number of such beacons along a front line for the dual purposes of providing radar bombing reference points and demarking the front line is therefore not feasible.

10.4.3 Microwave Systems

The BUPX's are lightweight radar beacons in the 10,000-mc region, designed to work with radars of the H2X type. The beacon reply is range coded to identify the particular beacon. The BUPS's are lightweight radar beacons in the 3,000-mc band, operating with search radars in that frequency range. Of the two combinations, the H2X-BUPX scheme is to be preferred, because the H2X radars are designed for bombing as well as for search, and because of the greater azimuth resolution possible at the higher frequency.

The advantages of microwave systems can be inferred from the previous discussion. The increased azimuth resolution permits BUPX beacons to be spaced as close together as ¼ mile and still be resolved at a distance of 6 miles, with the result that the number of targets for which individual reference points can be set up in a given area is much increased. One can read the bearing of the beacon from the aircraft, not merely tell whether or not it is dead ahead. Medium- and high-altitude bombing becomes possible, and offset distances can be increased for a given desired accuracy. Use of a number of reference beacons for front line marking is practical. The system gains in flexibility, since the H2X radar can be used for unaided radar bombing if desired, while all the low-frequency systems require that the beacons be in operation for a successful mission. The microwave beacons can be seen by all radars with which they are designed to work, whereas a Rebecca-Eureka pair must be tuned for each other on preassigned frequencies.

10.4.4 Tactical Use

Although beacon offset bombing did not see operational use in World War II, tactical trials were conducted by the AAF Board to develop methods of use and to determine accuracy. For low-altitude work, a technique was developed in which the first step was to assign the altitude, airspeed, and direction of approach to target for the bombing aircraft. The beacon was then located at the point such that if the aircraft, flying as briefed, released bombs at the instant it passed over the beacon, those bombs would strike the target. (For example, an aircraft flying at 100 ft altitude with a speed of 200 mph would require a beacon located 270 yd from target.) The air crew can determine the instant of passing the beacon, with the microwave system, by the fact that the beacon reply becomes, for a fraction of a second, a series of circles about the center of the display. With Rebecca-Eureka, the ground-beacon operator keys the beacon off the air at the instant the aircraft is overhead. The Rebecca-Eureka system, for an offset distance of 800 ft and a bombing altitude of 100 ft, gave as a typical result an azimuth error of 135 ft and a range error of 45 ft. The H2X-BUPX combination, for an offset distance of 2500 ft and a bombing altitude of 200 ft, gave an average radial error of 300 ft.

Medium- and high-altitude bombing is accomplished with techniques nearly identical with radar offset bombing. In one scheme, evaluated by the AAF Board, the aircraft flies toward the beacon on a briefed heading, the heading being corrected for drift angle so that the extended ground track of the aircraft passes through the beacon and the target. The bombing problem is set up as though the aircraft were to bomb the beacon. At the instant the beacon reply touches the bombing range circle, a stopwatch is started. The aircraft holds its airspeed and heading for the number of seconds required to fly from beacon to target, and then bombs are released.

Another method evaluated by the AAF Board involved the use of check points at known slant ranges from the beacon to synchronize the Norden bombsight. Results from 10,000 ft, using an offset distance of 2 miles gave bombing errors of approximately 2,000 ft.

The fact that a beacon gives a clear-cut signal, positively identified, suggests the possible future development of beacon offset bombing using an offset bombing computer.

10.5 HYPERBOLIC NAVIGATION SYSTEMS

10.5.1 Introduction

Hyperbolic navigation systems,[55] such as British Gee and American Loran, were not originally intended for blind bombing use. Their normal function is to provide an unlimited number of fairly accurate fixes for navigation over a large area, rather than the few very precise fixes required for blind bombing. The lattice or grid formed by the crossed position lines has, however, very appealing similarities to the cat-mouse course often flown with the various beacon systems (see Section 10.2.1).

These similarities suggest the technique of flying down one position line by keeping constant the observed time difference of one pair of pulses. The observed time difference of the other two pulses changes as the aircraft traverses the ground track defined by the first position line, and the bombs are released manually when this second time difference has reached the correct value.

In area bombing, with a hyperbolic navigation system, appropriate standard navigation charts are used, which are already overprinted with the computed lines of position. This has the advantage that no additional calculations need be made for an individual mission. A further advantage is that both the navigation to the target area and the release of bombs can be handled by the use of a single piece of apparatus and a single basic technique.

The obvious disadvantage of blind bombing with hyperbolic navigation devices is that the fix errors may be ten or more times those of beacon-ranging systems. This makes unprofitable any type of offensive bombing where the target is not distributed over a considerable area. Because of this fix inaccuracy, it is seldom worth while to apply any ballistic corrections other than an adjustment of the mouse reading to compensate for the forward travel of the bomb.

10.5.2 Navigation and Blind Bombing with Gee

Ground Station Arrangement

The basic Gee ground station arrangement consists of three stations spaced at intervals of approximately 70 miles, the line connecting them making an oblique angle of between 120 and 150 degrees. The center station is known as the *Master*, or *A* station, while those on either side are known as *Slaves*, designated *B* and *C* respectively. All three stations operate on the same radio carrier frequency, which is in the range between 30 and 80 mc. The Master emits short pulses at the rate of 500 per sec, every other pulse being marked by a slightly delayed, blinking, identification pulse known as the "ghost" pulse. The *B* Slave emits pulses at 250 per sec, the delay of each pulse behind the unmarked Master pulse being precisely maintained. The *C* Slave also transmits at 250 pulses per sec, each pulse occurring at a time shortly following the transmission of the Master's ghost-identified pulse. The time sequence of transmission is thus *A*-*B*-*A* (ghost)-*C*, indefinitely repeated. The timing delays and the distances between the stations are so chosen that the pulses are always received in this same order no matter where the receiver may be located. Only the *A* (ghost) pulse has a distinctive appearance, but the reception sequence provides positive identification of all pulses.

Airborne Instrumentation

By the end of World War II the Gee Mark II airborne set (A.R.I. 5083) was carried in nearly every Allied aircraft with a crew of two or more. For observing and measuring the time delays with the necessary accuracy, two basic presentations are used, giving essentially "coarse" and "fine" magnification. Figure 15 shows the appearance of the scope during the various manipulations. A single 5-in. cathode-ray tube is employed with linear horizontal sweeps and with signals appearing as vertical deflections, as in an A scope. The complete picture is traced out in 4,000 μsec; on the slow-sweeping "Main Time Base" this period is divided into two equal intervals, each of which is presented as a horizontal sweep with fast flyback. The two traces are separated vertically by a space of about 1 in. By manipulating the frequency control of the 150-kc crystal oscillator, an operator first places the two master pulses near the extreme left side of the two sweeps. The ghost-identified pulse is placed on the lower sweep and the other master pulse then appears above it on the upper sweep. The *B* and *C* slave pulses appear to the right of the master pulses, on the upper and lower traces, respectively. A coarse setting of the two expanded-sweep ("strobe") delays is then made; when the strobe is properly placed around its slave signal the slave signal is inverted and appears as a downward deflection (see Figure 15A).

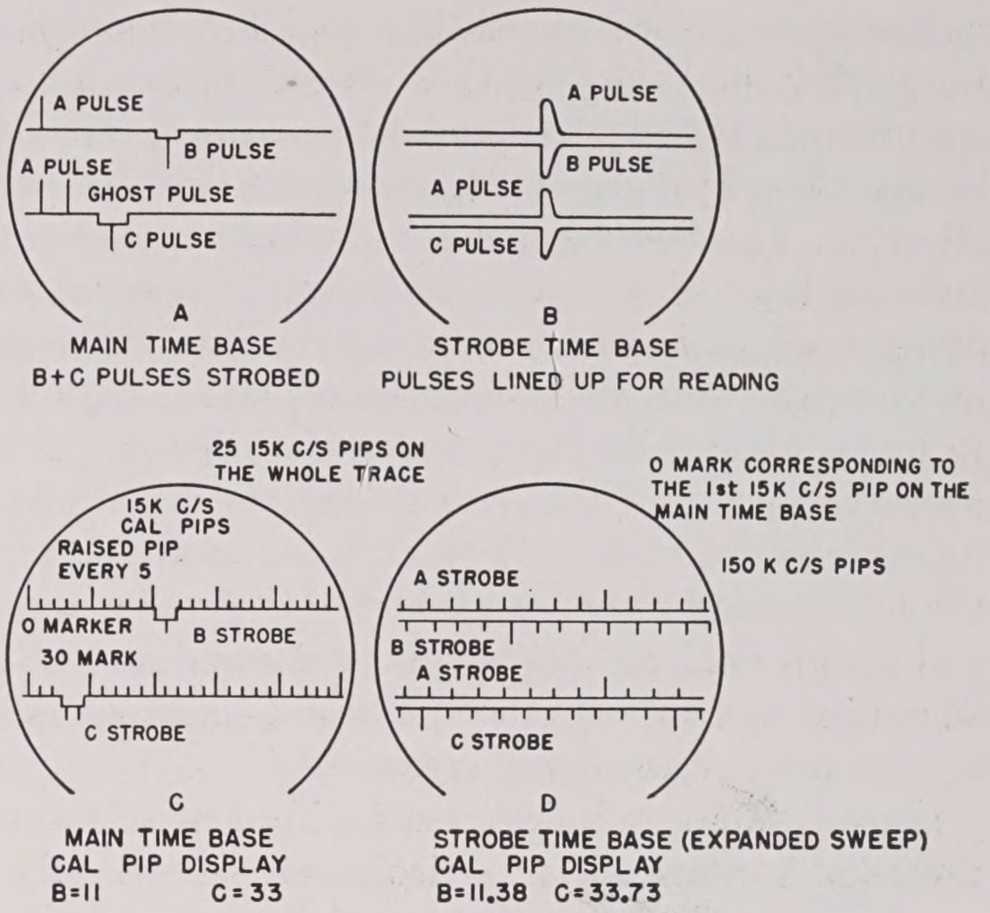

A PULSE
B PULSE
A PULSE
GHOST PULSE
C PULSE
A
MAIN TIME BASE
B+C PULSES STROBED
A PULSE
B PULSE
A PULSE
C PULSE
B
STROBE TIME BASE
PULSES LINED UP FOR READING
25 15K C/S PIPS ON THE WHOLE TRACE
15K C/S CAL PIPS
RAISED PIP EVERY 5
O MARKER
B STROBE
30 MARK
C STROBE
C
MAIN TIME BASE
CAL PIP DISPLAY
B=11 C=33
O MARK CORRESPONDING TO THE 1st 15K C/S PIP ON THE MAIN TIME BASE
150 K C/S PIPS
A STROBE
B STROBE
A STROBE
C STROBE
D
STROBE TIME BASE (EXPANDED SWEEP)
CAL PIP DISPLAY
B=11.38 C=33.73

FIGURE 15. Gee system indication.

The accurate setting and measurement is made with expanded sweeps of approximately 90 μsec duration. The picture consists of four such sweeps, one for each pulse, displaced vertically in two sets (Figure 15B). In each set the upper trace displays the master signal (*A*) with an upward deflection, while the second trace appears about 0.2 in. lower and displays the slave signal (*B*), with a downward deflection. The delay control is manipulated to place the slave pulse directly under the master signal, and when the same has been done for the other set of pulses the apparatus has stored the readings required for a fix. The two delay measurements are then made, by means of calibration pips derived from a 150-kc oscillator and subsequent dividing stages. The result is two four-figure numbers. The navigator is furnished with charts which bear overprinted lines corresponding to the first three figures of each number. Interpolation gives the two position lines whose intersection gives the fix.

Blind Bombing with Gee

It is evident that the Gee indicator is quite well adapted to flying the hyperbolic equivalent of a cat-mouse course, since one of the two delay readings is then kept constant. Position line curvature is not troublesome when the bombing run does not approach closer to a ground station than approximately 30 miles. The basic technique for flying the hyperbolic course with Gee is essentially the same as for flying a circular course with Gee-H. The principal difference is that, with Gee, the operator continues to make slight adjustments of the oscillator dial in order to keep the received pulses on the strobes. As in Gee-H and Micro-H Mark I, the operator gives the pilot verbal instructions such that proper course and proper heading will be achieved simultaneously. This process requires much skill and judgment and is a source of operational error.

Since Gee uses radio frequencies in excess of 30 mc, the reliable range for a particular altitude is only a few tens of miles greater than the line of sight distances from the ground station. The Gee service area is thus not much greater than that of the more accurate beacon ranging systems, and Gee has not been used extensively for blind bombing. It has, however, been used for dropping paratroops and has seen a great deal of service in RAF flare-dropping pathfinder operations.

In this latter technique, pathfinding aircraft navigate to the target area with Gee and release there a series of parachute flares. A master controller (so-called "Master Bomber") in a fast low-flying aircraft locates the particular flare most suitable as an aiming point and has it reinforced with other, distinctive, flares. The main bomber force then bombs visually on this flare. Much use was made of this technique by the Royal Air Force.

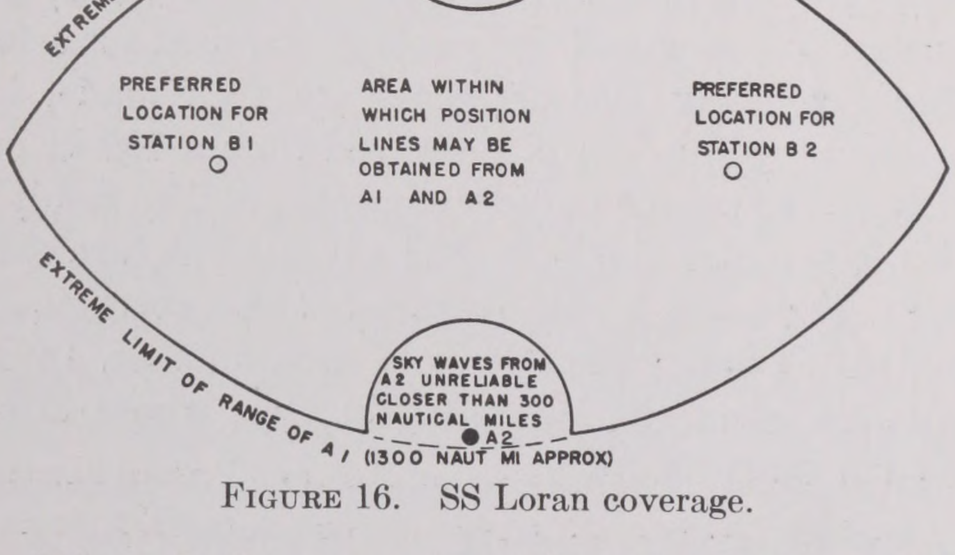

EXTREME LIMIT OF RANGE OF A2 (1300 NAUT MI APPROX)
A1
SKY WAVES FROM A1 UNRELIABLE CLOSER THAN 300 NAUT MILES
PREFERRED LOCATION FOR STATION B1
AREA WITHIN WHICH POSITION LINES MAY BE OBTAINED FROM A1 AND A2
PREFERRED LOCATION FOR STATION B2
EXTREME LIMIT OF RANGE OF A1 (1300 NAUT MI APPROX)
SKY WAVES FROM A2 UNRELIABLE CLOSER THAN 300 NAUTICAL MILES
A2

FIGURE 16. SS Loran coverage.

Although the accuracy of Gee becomes considerably less than that of beacon ranging systems at distances of more than 50 miles from the ground stations, its accuracy at shorter distances is quite comparable. This can be and has been a considerable disadvantage in that enemy aircraft carrying captured equipment are given a very accurate means of bombing the territory near the ground stations. This feature was exploited by the Germans in raids on London during the last weeks of February 1944. Rather alarming accuracy was obtained until the situation was recognized and the Gee stations temporarily removed from service.

10.5.3 Navigation and Blind Bombing with SS Loran

DIFFERENCES BETWEEN SS LORAN AND GEE

In comparing SS Loran and Gee, with reference to blind bombing use, SS Loran is found to differ in two major respects, one of which is somewhat of a disadvantage while the other is of very considerable advantage. SS Loran stations operate in pairs instead of triplets and the SS Loran airborne indicator (AN/APN-4) is adapted to making but one delay reading at a time. This means that, in a fast-flying aircraft, accurate running fixes must be made, which requires considerable skill. On the other hand, the radio frequency of approximately 2 mc makes possible a greatly extended usable range and a novel arrangement of ground stations, since, at night, ionospheric reflections may be used. In traveling between two separated points on the earth's surface these sky waves require somewhat more than 60 μsec longer than would the direct ground wave. Both the average value of this sky-wave delay and the probable deviation of a single measurement from this value have been experimentally determined as a function of range. The accuracy and constancy are sufficient to make one-hop sky waves very useful for synchronization and navigation. Since the received signals have been reflected from above, good reception is obtained at all altitudes down to the lowest, an advantage not found in any other radio navigation or blind bombing system. The height of the reflecting layer is sufficiently great so that the stations of a pair may be separated by as much as 1,200 nautical miles and still be synchronized at nighttime over a single-reflection transmission path. The area which is served by single-hop reception from a pair of ground stations lies between them and is bounded as shown in Figure 16. By suitably locating another pair of similar stations, fixes can be obtained over an extremely large area: as much as 1,000,000 square miles. Although the timing accuracy depends on the vagaries of ionospheric transmission, crossing angles are favorable over most of the service area and the position lines do not diverge seriously. The net result is that on the average one half of the fixes obtained will be in error by less than a mile, an accuracy which is substantially uniform over the service area. An important advantage is that since navigation is less accurate near the stations than over enemy territory, captured equipment will not be as useful to the enemy as was the case with Gee.

Airborne Instrumentation

The signals from different pairs of SS Loran ground station pairs are radiated at the same carrier frequency and are distinguished from one another by small precise differences in recurrence frequency. On each recurrence rate there are thus but two signals, one from each station of the synchronized pair. The airborne indicator is provided with a switch for making the signals of the desired pair stand still on the oscilloscope sweep while those of other pairs move at velocity sufficient to avoid interference. In other respects, the method of setting and measuring the received time differences is somewhat similar to that used in the Gee indicator, except that on the expanded presentation two sweeps are used instead of four. Only one time-difference measurement can be made at a time, and since a 100-kc crystal is used, the measurements are estimated to the nearest microsecond. To make the other delay measurement, on the second pair of stations, repetition of the three part measuring process is necessary, requiring between 1 and 2 minutes. This time has been reduced substantially by the addition of a switch and a duplicate set of delay controls so that in making a series of alternate observations on the two rates only small delay readjustments are needed. This modification was made and used by the RAF.

Blind Bombing with SS Loran

During the early months of 1944, four ground stations were installed by the Royal Air Force, aided by Radiation Laboratory personnel. The stations of one pair were located in Scotland and Tunisia respectively, while those of the other pair were located in Algeria and Libya. These four stations produced coverage over most of Europe as shown in Figure 17. Although the stations were ready several months earlier, it was not until September that they were placed in operation. At this time the RAF Bomber Command made immediate and large-scale use of the system and continued to do so until the end of the war. For a considerable period the SS Loran system provided the only means of navigation on raids deep into Germany and occupied Europe.

The Royal Air Force was the largest user of SS Loran, since the nighttime hours, when the sky-wave signals were useful, coincided with their period of most active operation. By March 1945, approximately 800 aircraft were fitted with Loran. In general, both Gee and Loran were installed but in some aircraft one set of mountings was used interchangeably for carrying either Gee or SS Loran, the choice depending on the nature of the mission. One group of the RAF made over 8,000 sorties with Loran-equipped aircraft and it is believed that on one-third to one-half of these sorties Loran was used for navigation. Gee was universally used for navigation in the region of the home airfields. In raids which were conducted on targets within Gee coverage, the use of Gee was preferred because of the greater ease of operation.

RAF Mosquito airplanes used SS Loran for several months on almost nightly nuisance raids over Berlin. On these raids both the navigation and bomb release were done with SS Loran. A total of over 13,000 sorties were made by RAF SS Loran-equipped aircraft. This, therefore, is the major example of the use of a hyperbolic navigation system for blind bombing on a target area.

10.6 NONBOMBING APPLICATIONS OF PRECISION BEACON NAVIGATION

10.6.1 Paratroop Dropping

Two nonbombing problems for which beacon bombing techniques are useful are paratroop dropping and photo-reconnaissance. The most widely used blind navigational method for troop carrier work in World War II was Rebecca-Eureka dropping zone location. The methods employed were entirely similar to those described in the section on beacon offset bombing (Section 10.4.1). Combat accuracy has been estimated from one-quarter to one mile average error in locating the center of a stick of paratroops. Operational use has also been made of Gee (*not* Gee-H) for dropping paratroops, but some Troop Carrier operations personnel have stated that Gee is not sufficiently accurate for locating the actual dropping zone although it is very useful in navigating to the right general area.

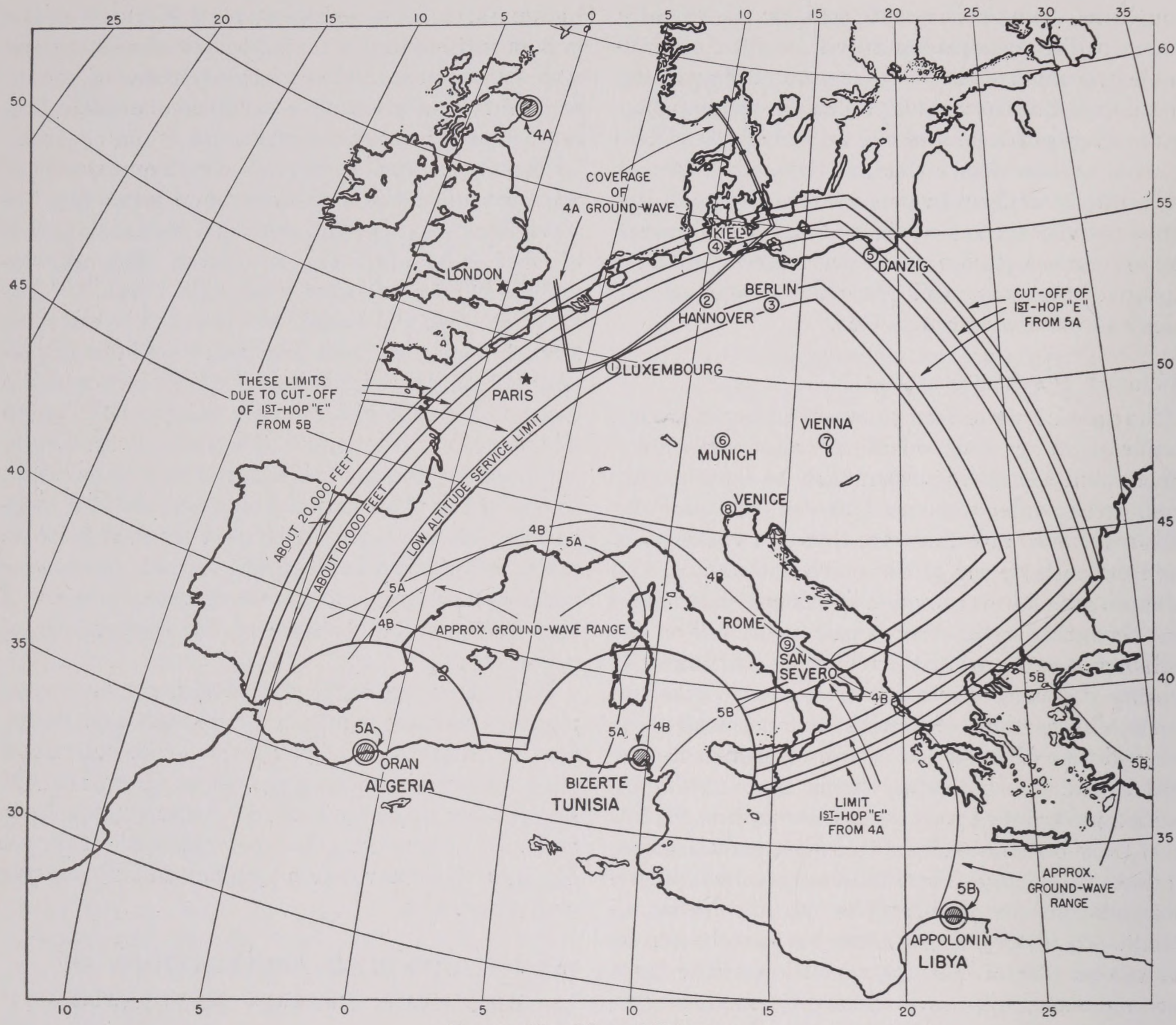

4A
COVERAGE OF 4A GROUND-WAVE
KIEL
④
⑤ DANZIG
LONDON
BERLIN
② HANNOVER ③
CUT-OFF OF 1ST-HOP "E" FROM 5A
① LUXEMBOURG
THESE LIMITS DUE TO CUT-OFF OF 1ST-HOP "E" FROM 5B
PARIS
VIENNA ⑦
⑥ MUNICH
LOW ALTITUDE SERVICE LIMIT
ABOUT 20,000 FEET
ABOUT 10,000 FEET
⑧ VENICE
4B
5A
APPROX. GROUND-WAVE RANGE
ROME
⑨ SAN SEVERO
5B
5A
ORAN
ALGERIA
4B
BIZERTE
TUNISIA
LIMIT 1ST-HOP "E" FROM 4A
APPROX. GROUND-WAVE RANGE
5B
APPOLONIN
LIBYA
25
20
15
10
5
0
5
10
15
20
25
30
35
60
55
50
45
40
35
50
45
40
35
30
10
5
0
5
10
15
20
25

FIGURE 17. Map of Europe.

10.6.2 Aerial Reconnaissance Applications

Several of the schemes previously described in this chapter have been adapted for use in aerial reconnaissance or mapping, and in principle any ground-controlled blind bombing scheme could be used for this purpose. The most highly developed method, however, uses Shoran. Special attachments have been developed for the Shoran airborne equipment to assist in the following two tasks:

1. Keeping the aircraft on course. For maximum economy it is necessary to have the aircraft fly a series of courses such that the aerial photographs completely cover the desired area, but do not overlap excessively. In Shoran mapping, a series of parallel straight lines are flown. In trials, it was found readily possible to keep the aircraft within 500 feet of a course, so that complete coverage was assured (from 15,000 feet) with 2½ per cent overlap.

2. Locating accurately one point on each photograph. If the aircraft is in straight and level flight and the axis of the camera is vertical, then the axial point on the photograph is directly below the aircraft. The aircraft position is known by recording the two beacon-to-aircraft ranges at the instant of exposure. If the aircraft is not in level flight, but the angles of tip and tilt are known, the point on the photograph which is directly below the aircraft can be determined.

The *Shoran Photo-Reconnaissance Recorder* unit can be installed in the airborne equipment in place of the usual bombing computer. It contains two variable speed motors which can be adjusted by the Shoran operator to keep the rate and drift pulses continuously in alignment, that is, to measure continuously the beacon-aircraft ranges. A recording camera is included, which takes an exposure each time the aerial camera shutter is opened, and records the readings at that instant of the following instruments: the two Shoran distance (range) counters, the barometric altimeter, an aerial clock with a sweep second hand, a flux-gate compass repeater, a tip and tilt indicator, a data card, and an exposure counter.

Mapping procedure is to fly to the area to be mapped, and by Shoran navigation to turn onto the first of the straight lines on which strip photos are to be taken. The Shoran operator keeps the pulses aligned and gives verbal instructions to the pilot to maintain the desired course. The taking of photographs, and the recording of the data necessary to locate each photograph, is automatic.

Tests by the Radar Laboratory, Wright Field, indicated that the geographical position of a point on an aerial photograph could be determined within 100 ft, using this method. Points so determined are, of course, referred to the Shoran ground stations, and hence are known in absolute position to no greater accuracy than that with which the ground stations are located. Relative to other points determined by use of the same pair of ground stations, the accuracy quoted is good if the separation between the ground stations is precisely known. This separation can be determined, to within less than 50 ft, by flying a Shoran-equipped aircraft between the stations.

Developmental work has also been done on automatic tracking devices, so the pulses do not have to be kept in alignment by manual adjustment, and on automatic computers which present the pilot with a PDI indication for flying straight line courses.

10.7 DEVELOPMENTAL TRENDS IN BEACON BOMBING SYSTEMS

10.7.1 General Deficiencies of Beacon Bombing

Several important limitations exist to varying degrees in all the beacon bombing systems described in this chapter. These are described in the following paragraphs.

Range

With all the radar-beacon schemes and with Gee the aircraft cannot bomb beyond the radar horizon. This limitation is so serious that in World War II the bulk of the blind bombing was done with radar bombing systems, although the accuracy of these bombsights was generally much less than that of beacon bombing schemes. It was unfortunately true that most of the important strategic targets were beyond the radar horizon of friendly territory.

Simplicity of Operation

Excellent results have been obtained with most of these equipments by expert crews under practice bombing conditions. Operational errors were usually from three to ten times larger. An equipment which requires extended and concentrated attention by highly skilled operators is limited in combat effectiveness. It is therefore desirable to make the equipment reliable and fully automatic, or at least to reduce the duties of the air crew to as few and as simple operations as possible.

Computer Design

Several of the beacon bombing schemes mentioned were limited in accuracy because the computer did not solve the bombing problem completely. In some cases, part of the computing problem had to be worked out by the man operating the equipment, thus increasing his duties and enlarging the chance of error. The most direct course to the target and the easiest to fly is a straight line, yet most computers permitted only an arc of a circle or a branch of an hyperbola. In no case did the computer output actually fly the aircraft, and in only a few cases was the pilot given his angular deviation (heading error) as well as his displacement error (distance to right or left) from the correct course. Only tentative schemes have been proposed for computers allowing approach to a target from any arbitrary direction.

Accuracy of range measurements, although far from perfect in any of these systems, is not listed here as a serious limitation, because the contribution of range error to bombing inaccuracy is small compared with the errors caused by lack of skill of the operators. With the best of present technique, range errors are roughly 15 yd.

10.7.2 Methods of Increasing Range for Beacon Systems

Two methods exist for increasing the range at which an aircraft, at a specified altitude, can work with ground equipment. The first of these is to elevate the ground equipment: the operating range is proportional to $(h_1)^{\frac{1}{2}} + (h_2)^{\frac{1}{2}}$ where h_1 is the height of the aircraft and h_2 is the height of the cooperating equipment. The second is to relay pulses from ground equipment to aircraft and back by means of airborne repeater stations.

Airborne Beacons

A simple example of the first method was proposed to extend the range of the Troop Carrier version of Micro-H Mark II. Here the aircraft flies at 500 ft altitude. Lightweight beacons were to have been suspended from barrage balloons. If the two barrage balloons were moored so that the beacon elevations became 1,000 ft, the range of the system would be increased by a factor of 2.4, that is, from 30 to 70 miles.

A more elegant proposal is to make airborne the two beacons in an H system. A means must be used then to locate the beacons in space, and the beacon reply must be coded to include the beacon position. In one case, it was proposed to modify Micro-H Mark III by making the two AN/CPN-6 beacons airborne. The beacon equipped aircraft was also to carry a precision radar and a GPI computer (see Chapter 9). The aircraft was to fly about a clearly defined radar reference point of known position. The GPI was to resolve the aircraft displacement from this point into rectangular coordinates. The y axis of this coordinate system is the line joining the reference point and the bombing target. To a first approximation (see Figure 18) the range from the bombing aircraft to the reference point is the range from the bombing aircraft to the beacon plus the y coordinate of the beacon. If the reply of the beacon is delayed by an amount which is proportional to y plus a constant (the constant being added to eliminate the possibility of negative delays), the bombing aircraft sees the beacon at an apparently fixed point. The bombing aircraft can therefore carry the standard H bombing airborne equipment and follow normal H bombing procedures.

If all three aircraft fly at an altitude of 30,000 ft the range of this system is 500 miles from the reference points. This increases by a factor of four the area that can be attacked if the reference points are in friendly territory. (In this event, the reference points might be marked by ground beacons.) However, it is also possible to choose clearly defined radar reference points in enemy territory, and then the area of attack is unlimited. The choice of suitable reference points is relatively easy, because any two points, each within 500 miles of the target, can be used, provided these points subtend an angle of at least 30 and less than 150 degrees as seen from the target. It should be pointed out that the beacon equipped aircraft can fly any course it chooses, provided it remains within approximately 20 miles of its reference point.

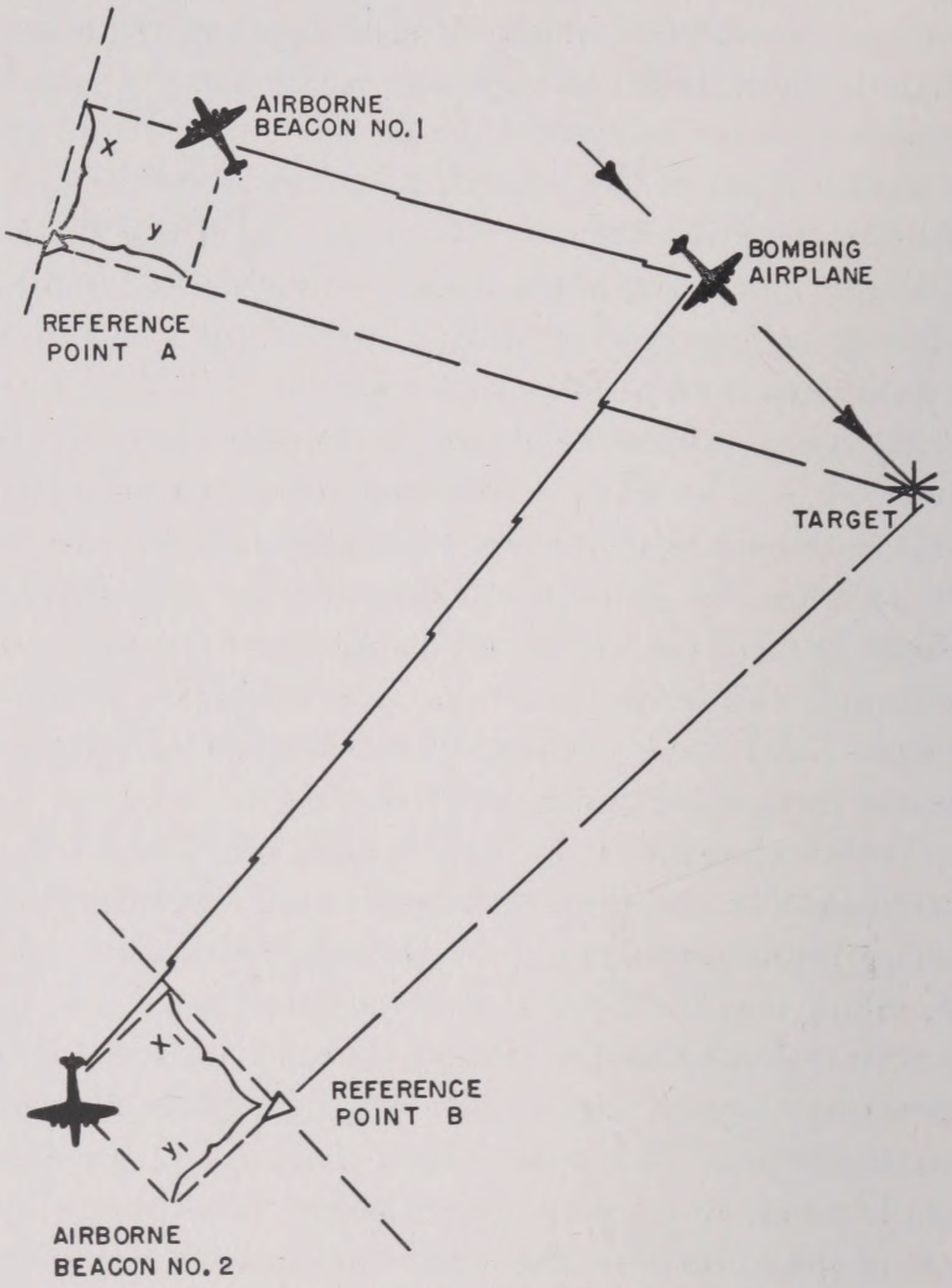


Figure 18. H system with airborne beacons.

The outstanding disadvantage of this scheme is that the coordinate systems have to be chosen for a particular target. Therefore only one target area can be attacked at a time. This restriction can be removed by the following scheme: let the coordinate axes be oriented at will, say, let the y-axis at each reference point lie in a north-south direction. Both the x and y outputs of the GPI are fed to the beacon. The beacon replies with three pulses, the first of which is undelayed, the second of which is delayed by an amount proportional to the x-coordinate of the beacon position, and the third of which is delayed by an amount proportional to the y-coordinate of the beacon position. The beacon reply then contains all the information required to locate the beacon position. Decoding equipment is carried in the bombing aircraft, and this information, when decoded, is supplied to a computer which computes the position of the reference point and the range from the bombing aircraft to the reference point. All the information needed to bomb an arbitrary target is therefore available in the aircraft.

REPEATER SCHEMES

A method for extending the range of Oboe Mark I, which saw a few operational trials, depends on airborne repeater stations. The Oboe ground station and Oboe bombing aircraft are unchanged (except in radio frequency) but a repeater aircraft flies along the line joining the ground station and the target. This aircraft carries two transmitters and two receivers. It receives and retransmits pulses from ground station to the bombing aircraft and vice versa. Since the repeater aircraft can operate to the radar horizon of the ground station, there is an increase of a factor of three in range using this system. Frequencies are so chosen that when a pulse from the ground station is received it is repeated to the bomber receiver only, and conversely.

With Oboe, difficulty was experienced because, in prototype equipment, a given receiver-transmitter pair was only 70 per cent reliable at operating altitude. Since the repeater system used three such pairs, the system was only 35 per cent reliable. The problem of getting normal Oboe in large-scale operation was very pressing at the time, so the repeater Oboe program never got beyond the stage of trial operations.

Oboe errors introduced by the repeater aircraft are of two kinds. First, the repeater aircraft may deviate from its assigned altitude, or may be displaced laterally from the course it is briefed to fly. For a representative situation, an error of 1,000 ft in altitude causes a bombing error of 40 yd, and a lateral displacement of 1 mile causes a bombing error of 7 yd. These errors are not serious. Second, as the repeater aircraft flies back and forth on its assigned track, the sum of the distances from the ground station to repeater and from repeater to a point at some given altitude over target does not remain constant. (If we consider the three points as forming a vertical triangle, the base line remains constant, but the sum of the lengths of the other two sides varies as the apex is moved.) If the repeater aircraft is at 35,000 ft and the target is at 500 miles from the ground station, and if the repeater aircraft stays between 150 and 250 miles from the ground station, the maximum error from this source is 90 yd. It is quite conceivable that this error could be substantially reduced by inserting a variable delay in the repeater link which depends on the aircraft position on its assigned track.

A similar repeater scheme was considered for use with Shoran.

10.7.3 Methods of Simplifying Operation

There are two ways in which the simplification of bombing procedure can be effected — either the bombing equipment can be made simple or it can be made automatic. Simple equipment with fewer controls provides less chance for maladjustment. Moreover, the simple equipment is lighter and more reliable in operation. It does have the disadvantages that less can be done with simple equipment and more depends on the skill of the operator. On the other hand, with automatic equipment, the operator's skill plays a minor role while the resultant equipment complexity is not a disadvantage if reliable operation is insured.

It is frequently overlooked that many "simple" equipments obtained their simplicity by requiring the operator to perform duties a machine could do better. For example, straight Gee bombing requires no airborne computer and only simple equipment; but the operator is required to work out, with pencil and paper, an approximate solution to the bombing problem while the aircraft is approaching the target. Shoran carries an airborne computer and is therefore more complicated, but the operator needs only to keep pulses aligned for the bombing problem to be correctly solved and the bombs released at the right time.

It is quite possible to conceive of an H system, for example, in which one simply sets into the airborne equipment the coordinates of the target and the bomb ballistics. The aircraft is flown to the general target area, the equipment is turned on, and then the duties of the air crew are over until bombs are away. Such an equipment would be complicated but could be made reliable and foolproof in operation provided the correct data were used. The additional weight would be justified every time more bombs were placed on the target, and would be justified many times over, each time a gross error was avoided.

It is evident that the same line of approach is a fruitful one for use in guided missiles. If the sole duty of the air crew is to get the aircraft to the target area, a guided missile could be built with the same equipment and so launched that it came into the control area.

10.7.4 Computer Design

Application of GPI

The GPI solution of the bombing problem (see Chapter 9) seems a hopeful one for use with beacon systems. The accuracy of the GPI solution depends on the accuracy and frequency with which fixes are supplied to the GPI. With beacons, highly accurate fixes can be supplied as frequently as desired. Use of a computer of the GPI type would permit a straight line approach to the target in any direction and facilitate the use of evasive action on the early part of the bomb run.

The computer should, of course, determine the bomb release point and actually release the bombs. The aircraft may be flown by the computer, using computer control of the automatic pilot, or by a pilot. The requirement, in previous bombing schemes, for a PDI indication showing the pilot not only his displacement from track but his heading error, has already been mentioned. In the GPI case, only one meter is required, since in the GPI solution it is necessary only that the aircraft be headed for the correct point and not that it approach on a specified track. The task of the pilot is therefore easier with the GPI computer.

Universal Bombsight

It is possible to design a system which would include a visual bombsight, a high resolution radar bombsight, and a beacon bombing equipment. Many of the components of these equipments are common and could be combined; for example, a single bombing computer might be used, with three different data inputs. The components would be so synchronized (as in Nosmo, Chapter 8) that when the beacon bombing method is being used, the visual bombsight is pointed at the target (whether the target is hidden or not) and so forth. An air crew would then have the opportunity to select the most useful of the three methods for any particular target, and could use the same equipment and many of the same techniques, whichever method was chosen. Further information on the beacons discussed in Chapter 10 can be found in the bibliography of Part II.[38, 39, 41, 46, 60–64, 88, 93, 107–110]

Chapter 11

GROUND-CONTROLLED BOMBING

11.1 PRINCIPLES OF GROUND-CONTROLLED BOMBING

11.1.1 Introduction

In the European Theater of Operations during World War II, a system of ground-controlled bombing was developed as a solution to the fighter-bomber control problem in the *tactical air commands* [TAC]. Initially utilized by IXth TAC, the use of such radar ground control spread throughout the various TAC's in the European and Mediterranean Theaters of Operations [ETO and MTO] and was applied to both medium and fighter bombers. It has been termed "Close-Support," "Close-Cooperation," or "Close-Control" bombing. The fighter-bomber groups found the system particularly useful as no equipment had to be installed in the aircraft. Extension of the control coverage required eventual introduction of airborne beacons for longer-range low-altitude operations.

The close-cooperation bombing system provides accuracy of control from equipment that is flexible and mobile. Its tactical uses range from the simple provision of navigational direction to the target area to accurate positioning of aircraft for medium level bombing under conditions of complete overcast. The problem of location of the target, navigation to the target area, computing the *ground-track-aiming-point* [GTAP], steering the aircraft towards the GTAP, and computing the bomb release point are all solved on the ground. The pilot flies the aircraft according to instructions radioed from the ground-controller and releases the bombs when so directed.

A ground-controlled bombing system contains five major components:

1. An automatic tracking radar which accurately measures the slant range, azimuth angle, and elevation angle of the target aircraft. Such a radar must have an excellent data transmission system which will provide the measured information in a form useful for controlling.

2. An automatic plotting table upon which the position of the aircraft is continuously recorded. It is desirable to have the aircraft track superimposed on a map of the area so that the relationship of the aircraft to its assigned target is always apparent.

3. A reliable communication link between the controlling radar and its target aircraft. An adequate communications network must also be provided for linking the controlling radar with supporting and associated ground units of the command.

4. A computer to determine accurately the GTAP and bomb release point by utilizing the output data of the radar.

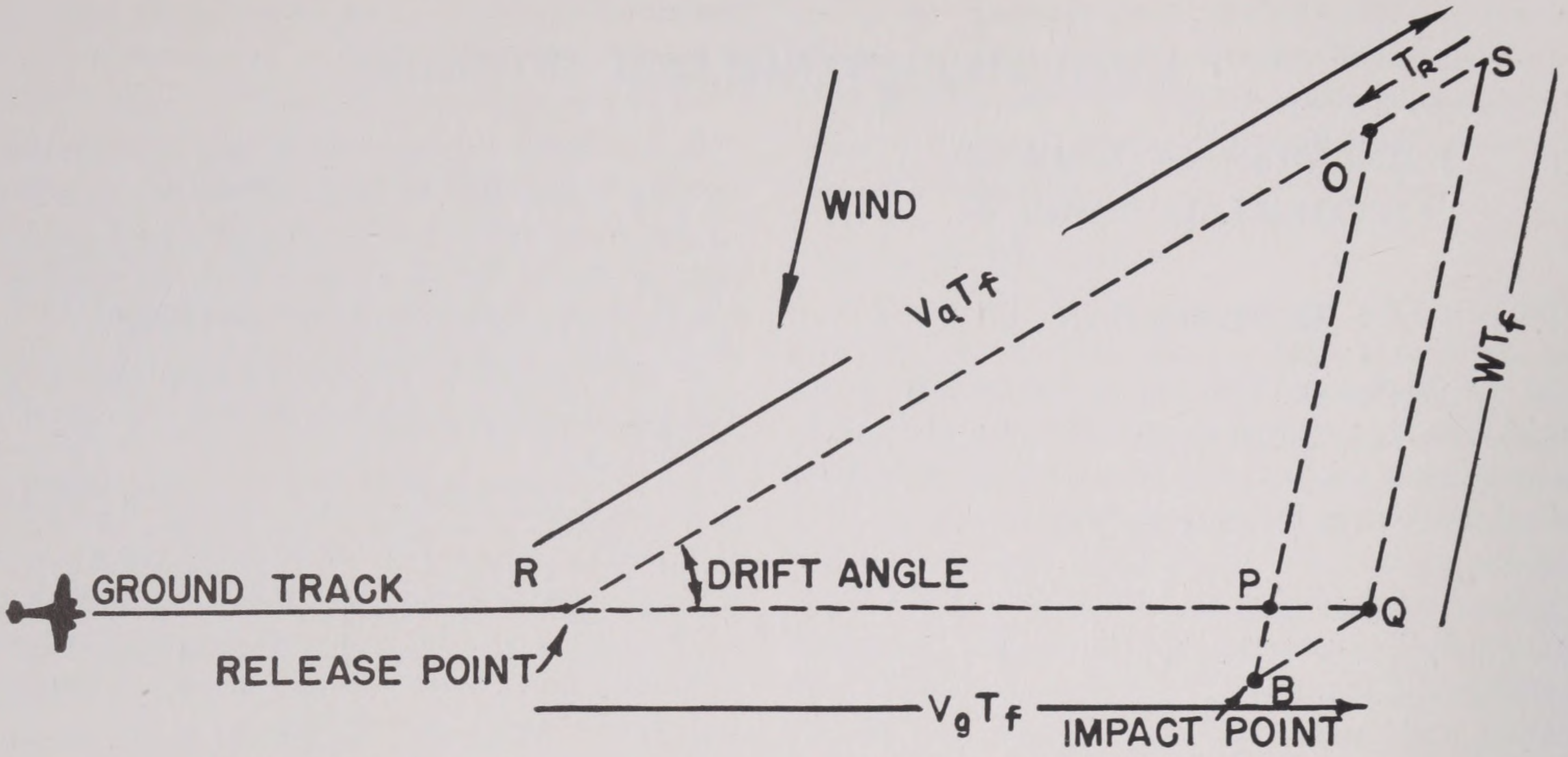
5. A beacon in the target aircraft for identification and for long-range low-altitude operation. Such a beacon utilizing multiple pulse interrogation and off-frequency coded response techniques increases the reliability and traffic capacity of the close-cooperation system (see Chapter 10).

11.1.2 Theory

In the ground-controlled bombing system, a complete solution of the bombing problem is simpler than in any other type of bombing device because $\mathbf{V}_g$, the ground velocity, can be determined directly. The geometry of the problem is shown in Figure 1. **RQ** represents the distance the aircraft would travel over the ground during the time of fall of the bomb if it continued on a straight course at constant speed after the bomb release point R is passed. **RQ** is the vector sum of **RS**, the distance the aircraft would travel in still air, and **SQ**, the distance it is carried by the moving air mass. $(\mathbf{RS} - \mathbf{T}_R)$ is the horizontal distance the bomb would travel in still air and $\mathbf{OB} = \mathbf{SQ}$ is the distance it is carried by the wind, with the result that the bomb impact point is B. The GTAP, P, possesses the geometric property that, with a given $|\mathbf{V}_a|$, $|\mathbf{T}_R|$, and $\mathbf{W}$, all ground tracks *must* pass through P for the bombs to strike B; the ground-controller therefore vectors the aircraft so that it is following the proper ground track through P at the release instant.

The position of P on the plotting surface can be calculated prior to the bombing run from meteorological and briefed data. Referring to Figure 1, it will be seen that P is displaced from B by an amount proportional to the wind vector and to the windward of the target, B. From the geometry, it is evident that:

$$BP = \left| \frac{\mathbf{W}}{\mathbf{V}_a} \right| \times | \mathbf{T}_R |$$



$\mathbf{V}_a$ = True airspeed
W = Wind
$\mathbf{V}_g$ = Ground speed
$\mathbf{T}_R$ = Bomb trail (in yards)

T_f = Time of fall of bomb
P = Ground track aiming point
B = Bomb impact point
R = Release point

FIGURE 1. Geometry of ground-controlled bombing as it appears to the ground-controller.

Note that BP is usually insignificant (of the order of 10 to 50 yd) compared with bomb dispersion errors and other errors in the technique. Unless the wind, (**W**), is strong (for example, 50 to 100 mph perpendicular to the ground track), BP can be neglected and B taken as the GTAP.

The position of R, the release point, is computed during the bombing run to the target by a measurement of $\mathbf{V}_g$ or $\mathbf{V}_gT_f$ directly on the plotting surface and a measurement of the aircraft's height with the radar. (Note: T_f depends on the height of the aircraft above the target and is obtained for a given bomb type from the same tables that give the trail $|\mathbf{T}_R|$.) A line is drawn connecting P and the aircraft's position. An arc of radius $BQ = |\mathbf{T}_R|$ is inscribed on the line, and $\mathbf{QR} = \mathbf{V}_gT_f$ is laid off from Q, thus establishing the bomb release point at R. When the aircraft reaches a point on the ground track corresponding to R on the plotting surface, the final release signal is given.

Just what fraction of the above procedure is performed automatically for the ground-controller depends upon the type of bomb computer utilized with the plotting table. Computers are discussed in Section 11.2.3.

11.2 EQUIPMENT AND TECHNIQUE

The ground-control bombing system has been described in complete detail in various publications.[24, 26, 28, 29, 45, 68–70, 100–105] Photographs of the SCR-584/M automatic tracking radar and the MC-627 automatic plotting table are shown in Figure 2A and B.

11.2.1 The Radar System

The SCR-584/M radar is capable of operating with aircraft not equipped with beacons at ranges up to 70,000 to 100,000 yd depending on type of aircraft. The range accuracy under these conditions shows a probable error of 20 yd. A probable error in azimuth angle measurement of 1.6 mils may be expected and the elevation angle probable error is also 1.6 mils for elevation angles greater than 3 degrees over a flat surface. With the standard SCR-584 radar, careless adjustment of the rather critical automatic tracking unit usually results in considerable deterioration of the angular accuracy. A new version of the SCR-584 known as the SCR-584X provides three times the angular accuracy, as it has a probable error of only 0.6 mil. Target aircraft equipped with beacons can be tracked and controlled out to the full 168,000-yd range of the plotter. A beacon has a response delay time that varies with the type of beacon and with the strength of the interrogation signal that triggers the beacon. This delay time appears as a range error unless response delay-time compensation is provided in the ground radar. In the case of the AN/APN-19A beacon, the pulse-interrogation unit provided as an addition to the MC-627 modification kit has a variable delay-time adjustment built into the circuit. Furthermore, the beacon response is coded so that the SCR-584 operator has positive identification of the aircraft he is tracking.

The accuracy of the plotting equipment associated with the MC-627 is sufficient to utilize fully the accuracy of the SCR-584/M and the data transmission system associated with it.

11.2.2 The Plotting Table

The MC-627 plotting table receives the radar range data from the SCR-584 position, converts it into the X and Y coordinates of ground range from the SCR-584 position, and plots the continuous airplane ground track on the plotting surface. The linear scale of the PT/61 plotter can be chosen to suit the operation. For "rough" navigation, scales of 1:500,000 and 1:250,000 are provided. A map of the chosen scale can be inserted beneath the tracing surface so that the position of the pen on the map indicates the corresponding position on the ground that is directly underneath the aircraft. The realizable accuracy of this relative presentation depends almost entirely upon the accuracy of the maps. In general, the errors in the best available 1:500,000 or 1:250,000 scale maps are an order of magnitude greater than the overall error caused by the equipment.

For expanded scale operations, the range of scales provided is from 1:20,000 to 1:112,000, and any scale between these limits may be used. An expanded scale map may be inserted and provision has been made for separate X and Y verniers to adjust for unequal map shrinkage, alteration in map materials, or printing errors. X-Y target coordinates are set into the table with calibrated parallax controls so that the target position lies at one of five arbitrarily selected points (the center of the surface or the center of any one of the four sides). The ground-controller vectors the aircraft so as to bring its ground track radially in toward the target point or the GTAP, and gives the release signal when the aircraft reaches the computed release point.

11.2.3 The Computer

Impact-Prediction Type

The procedure for obtaining the release point as outlined in Section 11.2.2 is called impact prediction (see also Chapter 8). The bomb release point is determined essentially by distance measurements on the plotting table, and the accuracy of the determination depends upon the constancy of the aircraft's velocity and similar factors throughout the bombing run. This method has, among others, the disadvantage that if the radar signals from the aircraft fade just prior to bomb release, a release signal cannot be given and the run must be repeated.

Synchronous Type

As the name implies, the synchronous type of computer involves setting up in a machine a position and a rate which correspond to the position and rate of the pen as it moves toward the target. The bomb-trail, time of fall, and target coordinates (or functions thereof) are also set into the computer (e.g., the Norden bombsight rate-end), which then calculates the bomb release point continuously. The function of the operator is to keep the indicator on the computer synchronized with the position of the plotting pen as it moves along the table, varying both the rate (V_g) and the position knobs as needed. The release instant is indicated to the controller by the coincidence of two indicators on the computer. The advantages of the synchronous over the impact-prediction type of computer are that it has a shorter time-constant, (i.e., less time is required to reach a new solution after a change in one of the variables), and it does not fail because of momentary fluctuations in position resulting from the loss of signals by the radar. It is also a reassuring device for the controller to operate, because the solution does not depend upon instantaneous measurements which are invariably poor when made under tension; instead, it depends on adjustments which can be checked and refined from time to time throughout the bombing run. Synchronous computers are much more complex than impact predicting computers.

In the European and Mediterranean Theaters of Operations, Norden sight techniques of a semi-synchronous nature were developed and utilized to fill an urgent need until a fully automatic computer could be produced. They were not continuously adjustable and consequently were not much superior to impact-prediction methods.

Automatic Computer (Synchronous)

An automatic computer was developed by the Bell Telephone Laboratories and the Radiation Laboratory for use with the MC-627 table. It provides com-

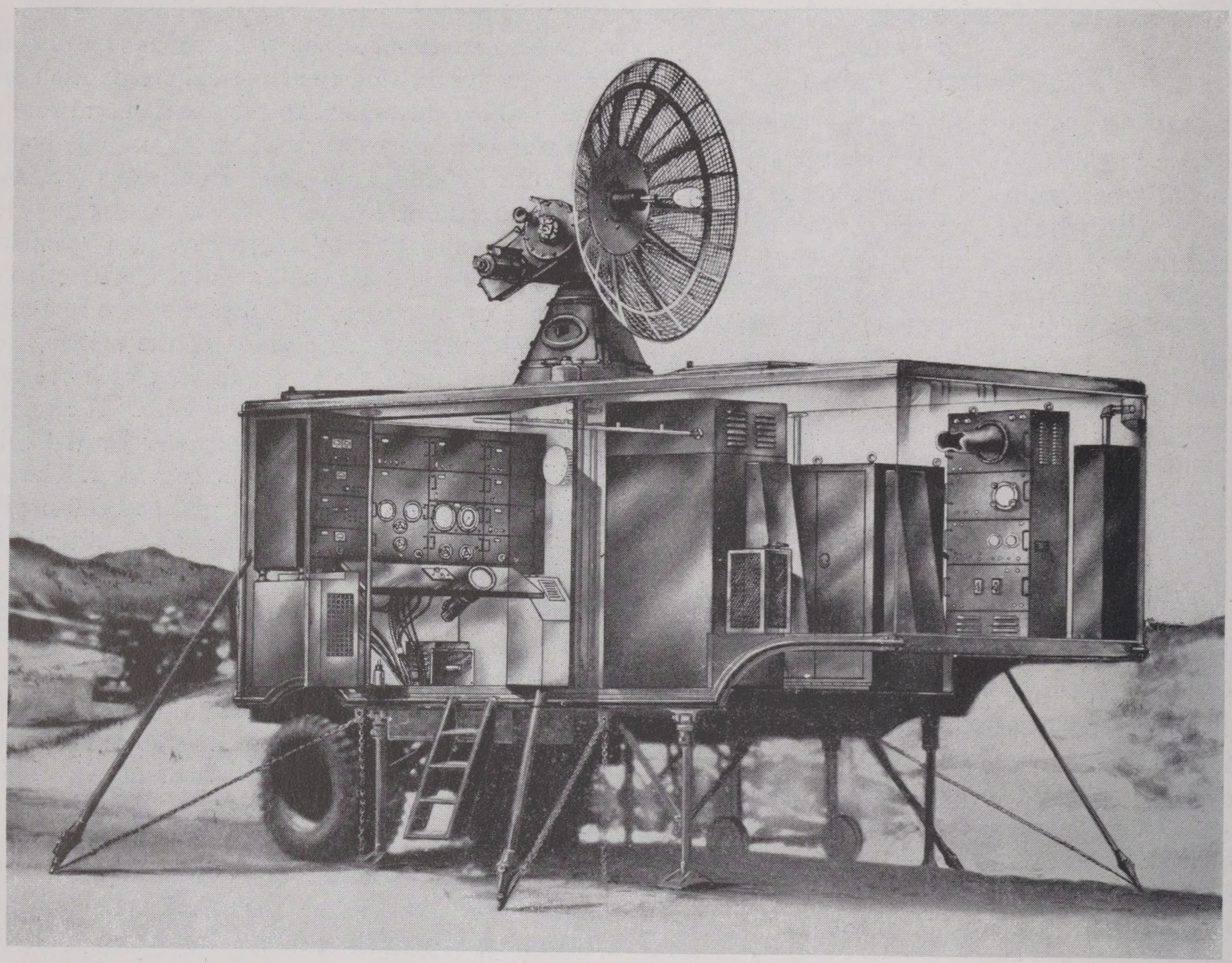


Figure 2A. Ghost view of SCR/584.

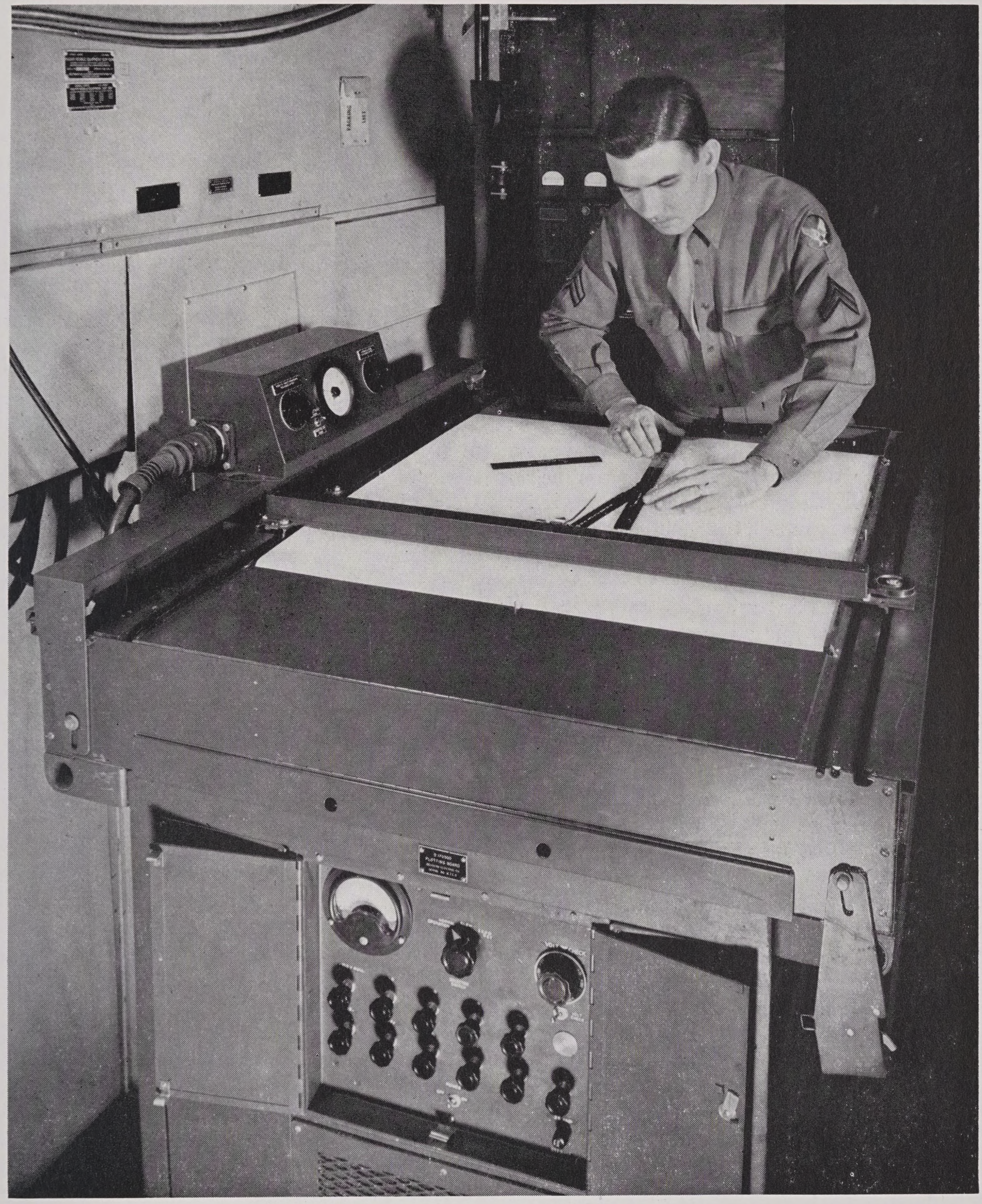


FIGURE 2B. Overall view of RC/294 plotting board.

pletely automatic computation when the bomb ballistics, true airspeed, altitude, wind velocity and direction, and target coordinates are set into it by means of knobs. The time constant of this computer is only 7 sec. Once adjusted for the problem, the computer then automatically provides the controller with information as to the angular correction required to correct the ground track of the plane. Also presented are the bearing angle to the GTAP, the ground speed toward the target and an indication of the time remaining before release when the airplane is within 100 sec of reaching the release point. The information furnished by the computer may be used by the controller in his voice control procedure or it may be sent out over the radio by an automatic steering angle correction circuit designed to operate a coded "on beam" indicator. This indicator is similar to that used with the airways A-N beams, but in addition it is provided with a sensitivity adjustment operated by the controller which effectively narrows the beam for closer control as the target aircraft nears the release point. During the last 10 sec before release a series of warning pips is provided, ending in a 3-sec pip, the end of which constitutes the release signal.

11.2.4 Vectoring

Voice-vectoring is divisible into two types, the first of which involves giving small angular corrections or new headings in order to bring the aircraft's projected ground track over the GTAP, while the second provides angular corrections or headings *plus* check-turns (S turns) so as to bring the aircraft down a *specified* line toward the target. The latter procedure is a standard *ground controlled interceptor* [GCI] technique and is less desirable because it is much more difficult for the pilot to accomplish with accuracy than the former. It also has the disadvantage that in making the check-turn, so as to produce a lateral displacement of the course by a few hundred feet, the pilot may turn as much as 20 to 30 degrees away from the line through the GTAP and, if he should happen to release the bombs under these conditions, they will miss the target by several thousand feet even though the aircraft is right on the prescribed line. In bombing, *heading errors* are likely to be more important than *position errors* at the release point.

11.2.5 Communications and Their Applications

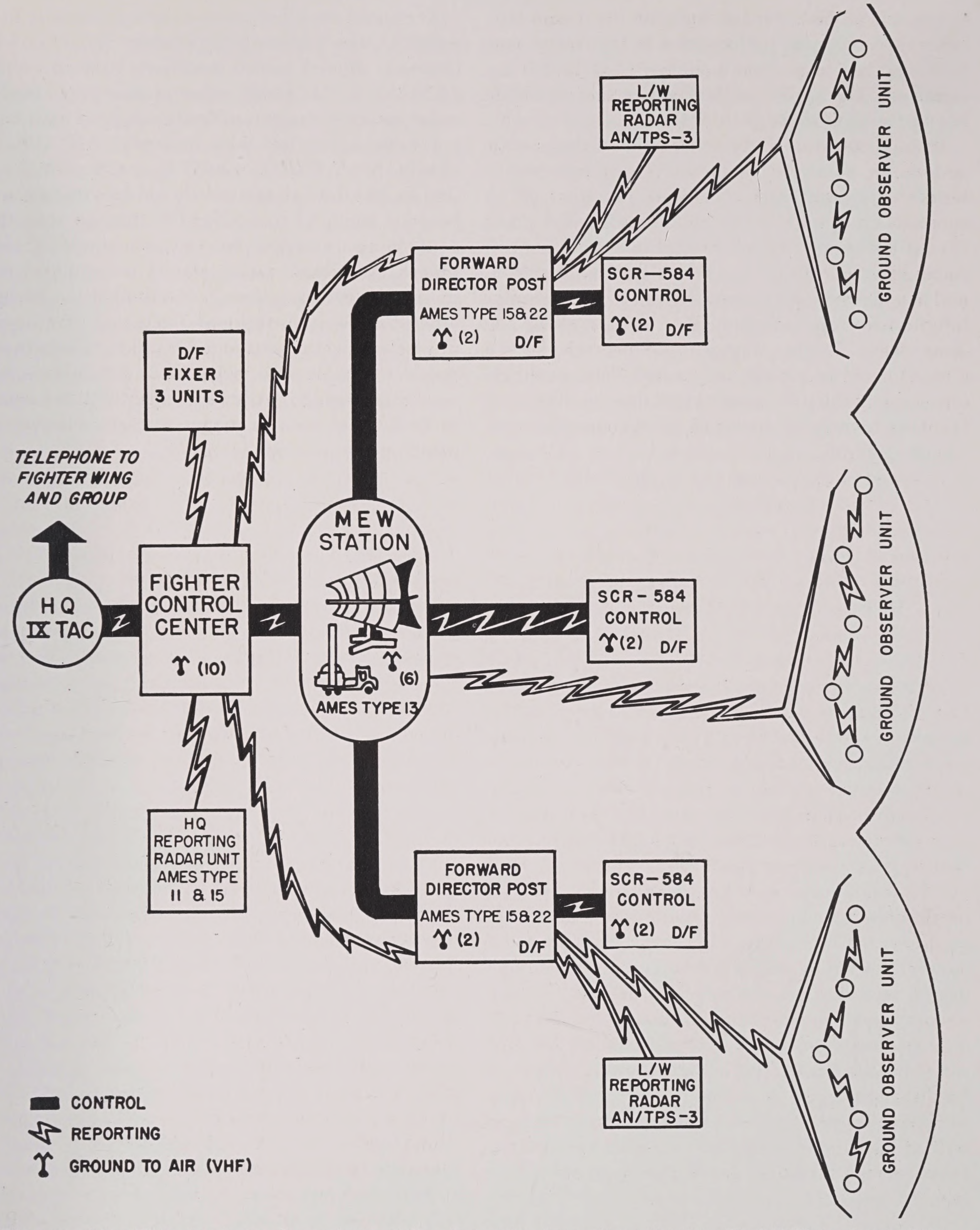
The transmission of intelligence is the key to the success of the entire system. The importance of reliable radio communication between the aircraft and radar is obvious. Good communication from the ground radar to certain other radars, airfields, and communication centers of the Tactical Air Command is also vital; for over these channels come daily, or oftener, orders for the missions, coordinates of the targets, identification codes of the aircraft, ground-to-air communication channel frequency assignments, meteorological data, data on bomb load and type, take-off and over-target schedules, position of the bomb line, flak areas and forbidden areas, and other necessary operational and administrative information. In this connection it must be emphasized that communications play a vital part in the actual bombing missions, because the aircraft or flight is controlled up to the rendezvous point and after bomb release by long-range GCI or MEW radars. Thus, the aircraft remains under tight ground control as it is handed from radar to radar or station to station.

Both land-line and f-m radio or microwave communications are necessary in order to handle all situations. When the front is static, land-lines are preferred to radio channels because they are somewhat simpler to maintain and their security is better; the radio channels are then used for emergency standby. In advancing or retreating situations, it is difficult or even impossible to maintain land-lines, and radio channels or couriers become the means of communication.

11.2.6 Large-Scale Unified Control Systems

In the previous section it was hinted that the SCR-584 system is only the "sight" to a tremendous "gun" comprising all the radars, radios, land-lines, control centers, etc., of the Tactical Air Command. One of the most successful of such large-scale systems existed in the IX Tactical Air Command, 555 SAW Battalion, and is represented in part in Figure 3.

The fully-engineered control radar of which the SCR-584/M is the prototype never actually saw action. This final conception of a close-cooperation unit is termed AN/MPQ-2 and is accompanied by adequate tables of organization and equipment that include all radar, beaconry, VHF, f-m radio-teletype and telephone equipment needed to do the complete job. Sufficient mobile equipment and spares should be included to make the unit self-sustaining and fully mobile.


L/W
REPORTING
RADAR
AN/TPS-3
FORWARD
DIRECTOR POST
AMES TYPE 15& 22
(2)
D/F
SCR—584
CONTROL
(2)
D/F
GROUND OBSERVER UNIT
D/F
FIXER
3 UNITS
TELEPHONE TO
FIGHTER WING
AND GROUP
HQ
IX TAC
FIGHTER
CONTROL
CENTER
(10)
MEW
STATION
(6)
AMES TYPE 13
SCR-584
CONTROL
(2)
D/F
GROUND OBSERVER UNIT
HQ
REPORTING
RADAR UNIT
AMES TYPE
11 & 15
FORWARD
DIRECTOR POST
AMES TYPE 15& 22
(2)
D/F
SCR-584
CONTROL
(2)
D/F
L/W
REPORTING
RADAR
AN/TPS-3
GROUND OBSERVER UNIT
CONTROL
REPORTING
GROUND TO AIR (VHF)

Elements of the 555th signal aircraft warning battalion fit together in a pattern like this. The MEW site, heart of the control setup, is usually within 10 to 30 miles of the front lines. Tactical missions can be directed from there, the two forward director posts, and the three SCR-584 control centers.

FIGURE 3. A typical fighter and fighter-bomber control system for a tactical air command.

In such unified systems some of the long-wave, older type radars as well as some of the recent ones have had real use. Height finders (AMES 13) accompanied the MEW, while direction finders (SCR-575) accompanied the SCR-584's.

In supplementing and further modernizing such a system, it would be desirable (1) to incorporate beacon equipment with the MEW function; (2) to supplant all the AMES-15 radars with AN/CPS-6; (3) to tie together by relay radar in a main control room all TAC, MEW, and AN/CPS-6 information, and in a master control room (by relay-radar) similar information from all the other TAC's along the Army front. In this way, airtight control over all aircraft could be rigidly maintained. This would reduce greatly the possibility of lost aircraft strafing or bombing friendly troops or of AA defenses firing on friendly aircraft.

For round-the-clock ground control bombing to be practical, the TAC radar equipment should also include (1) ground control approach landing systems (AN/MPN-1) at every major airstrip; (2) airborne radar reconnaissance squadrons equipped with moving vehicle detectors like Butterfly (AN/APS-26), Firefly (AN/APS-27), or AMTI (see Chapters 23 and 24). In addition, all aircraft should be equipped with beacons (such as the AN/APN-19A) so that they could be easily located, tracked, or identified at great ranges. All ground radars should be equipped with moving target indicators (even though the friendly aircraft are beacon-equipped), so that enemy aircraft can be readily spotted and identified. The airborne radar reconnaissance squadrons and night-photo squadrons should be operated under SCR-584 control so that the targets they spot can be accurately located on the situation map.

Chapter 12

APPLICATION OF RADAR TO TOSS BOMBING

In certain bombing and fire-control efforts it has been deemed desirable to use visual sighting but to supplement this with radar range information. The logic of such a view lies in the fact that, whereas visual sighting can be reasonably accurate under favorable conditions and can often not be equaled with even very complicated radar equipment, radar range data will, in general, be far more accurate than such data obtained by other means and can be made available by the use of relatively simple radar equipment. Consideration of the use of radar range in airborne gunnery will be made in Part IV of this volume, so we will restrict our attention here to bombing problems.[1]

An obvious application of radar range to visual bombing is the use of radar altitude (range to the ground) in adjusting a visual sight, such as the Norden, for a level bombing run. This procedure, which has seen considerable use because of the availability of SCR-718 altimeters, would appear to have considerable advantage over the use of a pressure altimeter in operations above level terrain, since its use would obviate knowledge of the barometric pressure at ground level and the necessity of converting indicated altitude to true altitude. For possible "universal" bombsights, which permit a bombing run during which the altitude is changing, it would appear to be particularly convenient to use the continuous, reliable altitude information that a radar device can provide when over level terrain. Such obvious applications of radar range to the bombing problem are reasonably straightforward and it is therefore intended to devote the remainder of this chapter to a review of a type of bombing called toss bombing, in which, as will be seen, there is the possibility of a more intimate and unique use of radar range. Before taking up this particular problem in detail however, it might be pertinent to mention in passing the so-called "Sniffer" equipment (AN/APG-4), which is an f-m radar operating in the 73-cm band. This equipment, by exploiting the Doppler effect (see Section 23.2.1), is capable of measuring a suitable linear combination of range and range-rate to semi-isolated targets over water and so permits automatic bomb release in a very low altitude level bombing run with altitude supplied, if desired, by an AN/APN-1 altimeter. In this connection attention is also drawn to the f-m equipments AN/APG-22 and AN/APG-24 of recent design, which could be used to provide range and range rate information.

12.1 ANALYTICAL DISCUSSION

12.1.1 Description of Toss Bombing

In the type of bombing attack which has been given the name toss bombing an airplane makes a straight approach towards the target, but pulls up before releasing the bomb. Release should occur when a velocity component has been attained away from the previous direction of approach adequate to compensate for the gravity drop which the bomb will experience in its subsequent motion to the target. This type of attack is illustrated in Figure 1 in which two diving approaches are shown.

If one compares this type of attack with a conventional level bomb run in which release is made at about the same range from the target, it is apparent that, in some instances, the trajectory of the bomb will be noticeably flatter for the toss bombing case. From the point of view of permissible tolerance in ranging accuracy, such a flat trajectory would be an advantage in an operation against a target of considerable vertical extent or, with proximity fusing, against a target in the air. A second favorable feature which has been claimed for the toss bombing technique is that at the time the bomb is released the pilot has already commenced a maneuver which will soon take him away from dangerous proximity to the target. Aside from these alleged advantages of toss bombing — advantages whose validity will depend upon the exact nature of the attack — it is clearly a very simple technique which can be used to advantage by the pilot of a single-seat airplane. Attack bombers or pursuit aircraft would appear to be particularly suitable for a toss bombing attack and it might be desirable in operations against some types of targets to supplement such bombing with machine gun fire. Despite the advantages claimed for the flatness of the trajectory of the bomb, the pull-up and subsequent bomb release must be controlled quite accurately in toss bombing. Although sponsorship of a toss bombing program has fallen in large measure to Division 4 of the National Defense Research Committee [NDRC], the possibility that radar can be a real aid makes it appropriate that the

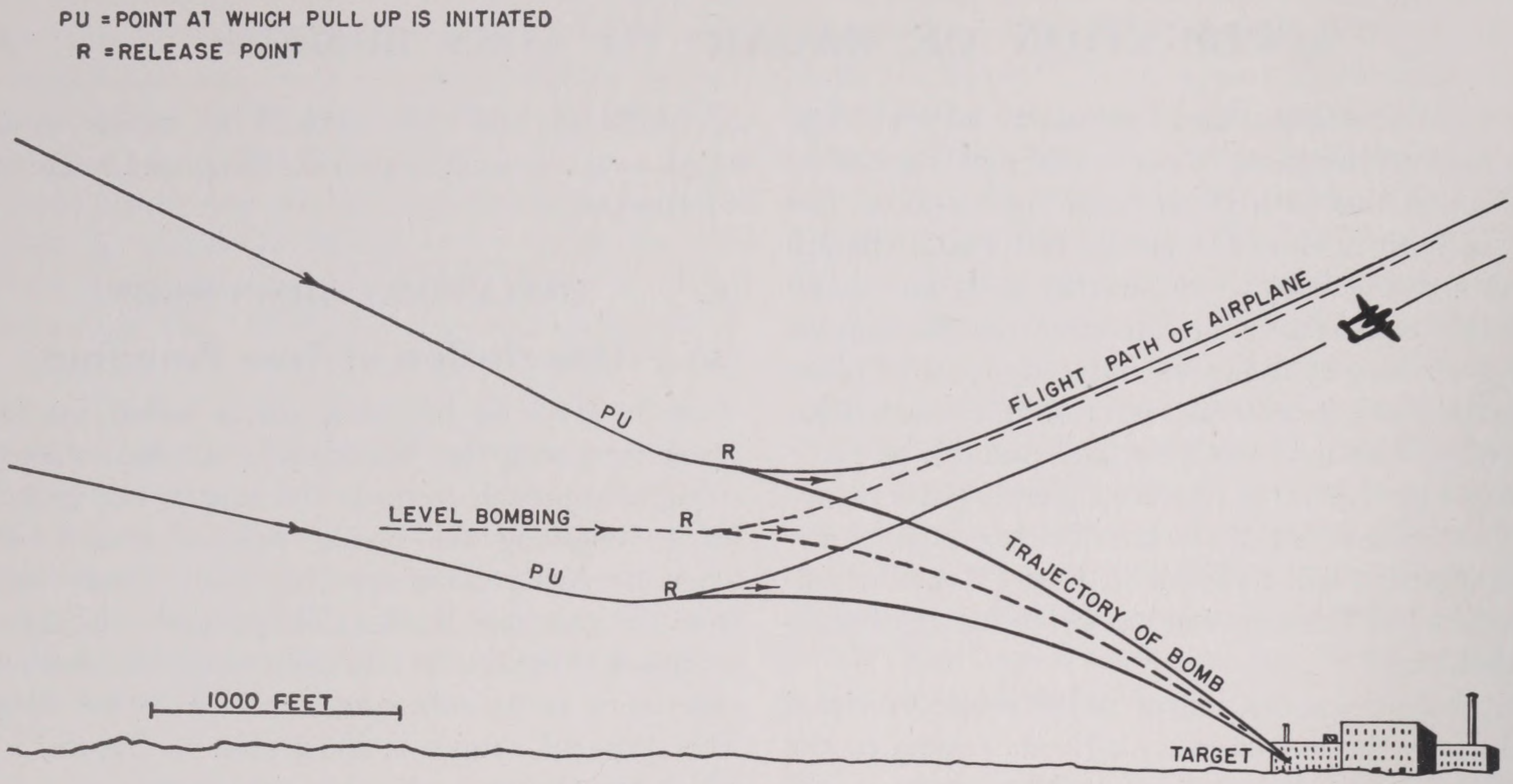


FIGURE 1. Toss bombing attacks.

theory of the method be reviewed and the instrumentation discussed in the following sections.

Tactically, toss bombing attacks might be distinguished according to whether the target is an airborne one, such as a bomber formation which it is desired to break up for possible subsequent fighter action, or whether it is a surface target. Alternatively, one might distinguish between a level approach and the more general diving attack. In practice, a level approach will be preferable against airborne targets, whereas an attack against a surface target will almost always be necessarily a diving approach. As will be indicated, a ground target becomes for the purposes of analysis a moving one when there is a wind, so there is, in principle, little distinction to be made between aerial and ground targets.

When the target is a moving one, or when there is a wind, it is desirable for the pilot to "lead" the target so as to achieve a straight collision course prior to pull up. This applies to both azimuth and elevation, although under some circumstances compensating factors (see "Effects Resulting from Attacking on a Pursuit Course" in Section 12.1.4) may result in good accuracy being obtainable when a pursuit course of small curvature is used. In attacking an enemy bomber formation, however, it would appear to be highly desirable to avoid the necessity of estimating what would be a large lead and attempt a straight head-on attack.

12.1.2 Elementary Analysis of Toss Bombing

LEVEL APPROACH

In analyzing toss bombing problems an important concept is the time to the impending collision. This quantity, which is commonly designated T_c, is, *at every instant of the approach,* equal to the range to the target divided by the rate of closure. In the case of a level attack the problem essentially is to give the bomb an upward velocity (measurable electrically or mechanically as the time integral of the upward acceleration) which will cause the bomb to return to its original altitude in the time T_c. If the forward motion and displacement from the original flight path during the pull-up are ignored for the moment, such a consideration would lead one to the conclusion that in a pull-up begun when the time to the collision has a value T_c, release of the bomb should occur when

$$T_c = \frac{2}{g}\int_0^{T_p} a\,dt. \qquad (1)$$

Here a is the upward acceleration; g, the acceleration of a freely falling body; and T_p is the time consumed in the pull-up before bomb release.

As the attacking aircraft will progress forward during the pull-up and also gain some altitude, the preceding equation must be modified to the following form:

$$T_c = \frac{2}{g}\int_0^{T_p} a\left[1 + \frac{g}{2a} + \frac{1}{2}\left(\sqrt{1 + \frac{g}{a}} - 1\right)\right]dt, \quad (2)$$

where T_c, as before, represents the time to collision at the start of the pull-up. In this expression the second and third terms of the integrand provide the corrections, respectively, for the two effects just mentioned. (The second term, of course, would not be required if T_c represented the time-to-go at *release* rather than, as here, the value just prior to the pull-up. This term has merely the effect of increasing the right hand side of the equation by the quantity T_p.) In deriving equation (2) the assumption is made that the component of velocity along the original flight path remains constant and that, for obtaining the final term of the integrand, the acceleration may be taken as constant during the pull-up. Such assumptions may require further consideration later, but the relation expressed by equation (2) has been frequently referred to since February 1943. (For an early analysis of toss bombing, reference is made to a series of four reports by the Ordnance Dept., U.S. Army.[89–92] An extensive series of papers on toss bombing has been issued by the Lukas-Harold Naval Ordnance Plant.[106])

Equation (2) illustrates the important role which the quantity T_c plays in toss bombing and indicates the essentials of the problem to be solved. Basically what is required is, first, a means for obtaining T_c and, second, a device for tripping the bomb release circuits when the integral has attained the proper value. Means by which these things can be done will be discussed in a later section, but it may be well at the moment to continue with the analytical aspects of the problem.

It is convenient to introduce a quantity K to serve as a measure, in terms of g, of the spatial acceleration *plus* the gravity component; that is, for the level approach considered at present,

$$K \equiv \frac{a+g}{g} = \frac{a}{g} + 1. \quad (3)$$

Equation (2) can be rewritten in terms of K:

$$T_c = \int_0^{T_p} [K + \sqrt{K(K-1)}]dt. \quad (4)$$

It is interesting to note that, as shown in ref. 92, the integrand of equation (4) may be approximated quite accurately by a *linear* function of K if this will facilitate the instrumentation. A plot of this integrand and of the proposed linear approximation is given in Figure 2. Thus, for values of K between 1.5 and 4, we can replace equation (4) by the following approximate condition for release:

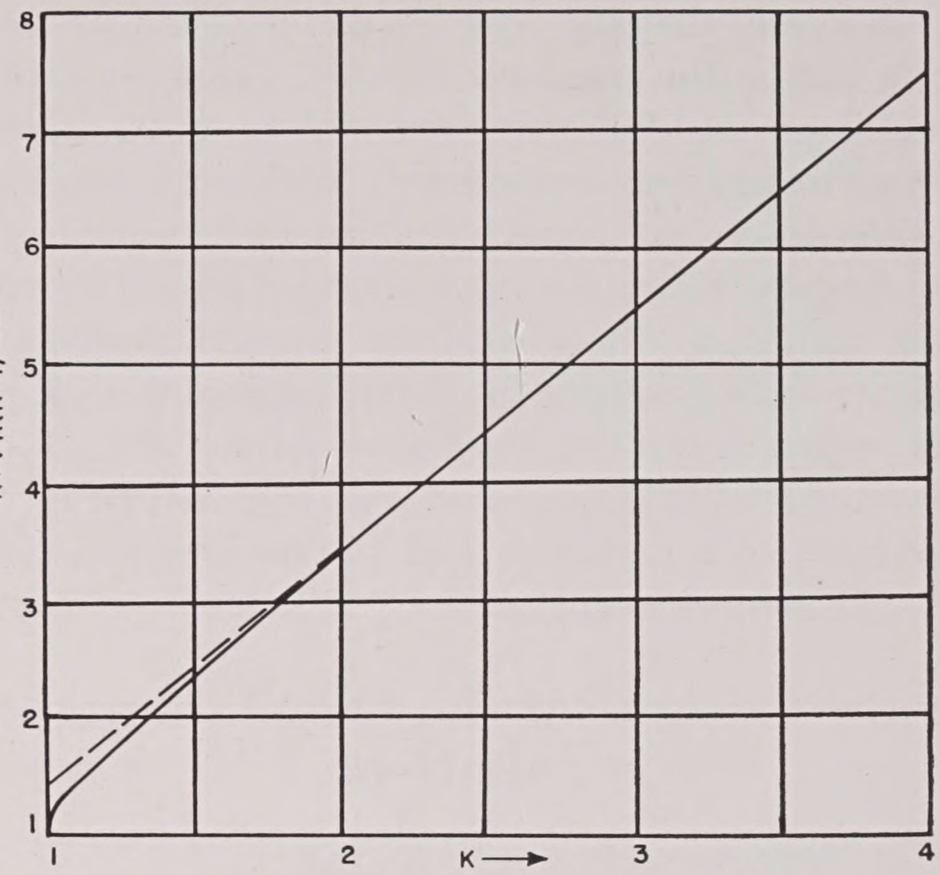


FIGURE 2. Plot of the integrand of equation (4). For comparison the dashed line illustrates the proposed linear approximation (2.035) (K-0.322).

$$T_c = \int_0^{T_p} 2.035(K - 0.322)dt, \text{ for } 1.5 \leqslant K \leqslant 4. \quad (5)$$

DIVING ATTACKS

In analyzing a diving attack we find that the airspeed of the airplane in its dive is involved explicitly in addition to affecting the value of T_c. With assumptions similar to those for a level approach we find that the toss bombing equation must be modified to the following form for a diving attack making an angle α with the horizontal.[19]

$$T_c = T_p \times [K + \sqrt{K(K-1)}] \times \frac{1}{\psi(\alpha, K, T_c/V)}, \quad (6a)$$

where

$$\psi = \frac{K + \sqrt{K(K-1)}}{K + \sqrt{K(K - \cos\alpha)}} \times \frac{\cos\alpha}{\beta} \times [\sqrt{1 + 2\beta} - 1], \quad (6b)$$

and

$$\beta = \frac{T_c(K - \cos\alpha)\, g \sin\alpha}{V \cdot K}. \quad (6c)$$

Note: K is defined as the total number of g's—acceleration and component of gravity—perpendicular to the original line of flight, so that $(K - \cos\alpha)\, g$ is the spatial acceleration of the airplane.

It is seen that the function ψ represents a correction factor for equation (4) and takes on values running from 1.00 for $\alpha = 0$ to 0 for $\alpha = 90$ degrees. ψ is primarily a function of α with only small dependence on T_c/V and virtually no dependence on K. A plot showing the dependence of ψ on α for various values of T_c/V (and for $K = 4$) is given in Figure 3. In practice, the dependence of ψ on K can be neglected and the effect of variations of T_c/V can be adequately compensated if T_c is measured by the charging of a capacitor and the nonlinearity of the charging curve is exploited.[19]

12.1.3 Critique of the Elementary Analysis

THE EFFECT OF PULL-UP ANGLE

Before considering mechanisms which can be employed to measure T_c and the other pertinent quantities and to give the signal for bomb release, it may be well to review briefly the possible errors introduced by some of the assumptions made in deriving the general toss bombing equation (6a) and similar relations. One assumption which can lead to appreciable error is that the pull-up acceleration, which is initially perpendicular to the collision course, remains constant in direction. This, of course, implies that the velocity component along the initial direction of approach remains constant. Actually a more realistic assumption would take the airspeed constant and the acceleration directed perpendicular to the instantaneous direction of flight — in practice, the total acceleration (including the component of g) measured along such a direction would be the quantity most readily measurable by equipment mounted in the airplane.

The result of assuming that the acceleration is normal to the initial direction of flight will be that the bombs actually released will fall short of the target, particularly if the pull-up is begun at long range. A quantitative study of the amount of horizontal range error introduced has been made at the National Bureau of Standards.[5,6] Approximate formulas are derived for the error and curves given to show the conditions under which a 100-ft range error will be obtained. Table 1 illustrates the information given by these curves. In general, the variation of this slant range is approximately as $V^{3/2}$ when α is large (compared to the circular pull-up angle) and as $V^{4/3}$ when α is zero or small. Similarly, if we are interested in the values of these ranges for horizontal errors other than 100 ft, we may use the approximate relation [6]

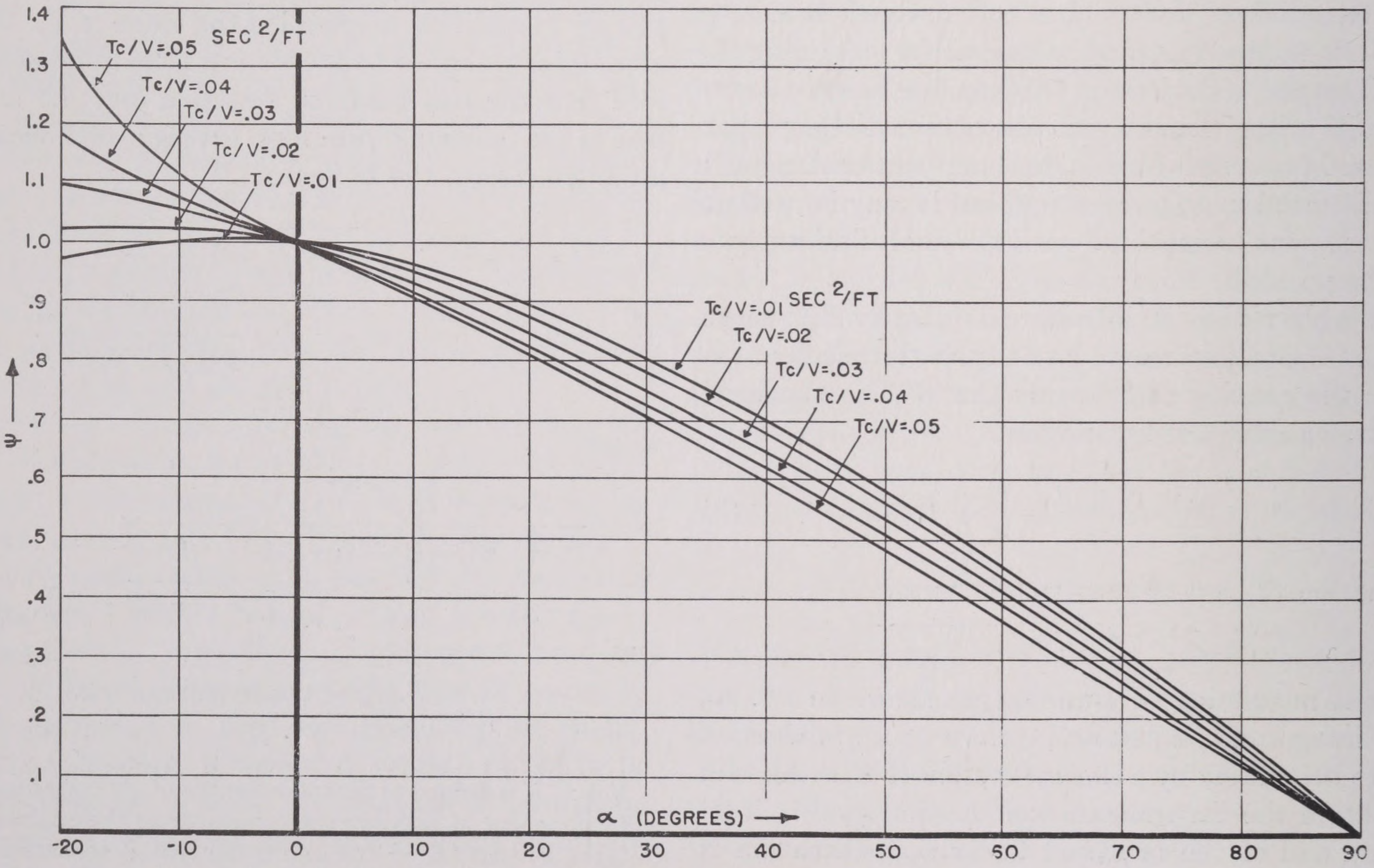


FIGURE 3. Plot showing the dependence of ψ on α for various values of T_c/V. ($K = 4$).

that these errors vary approximately as the fourth power of the range when α is large and as the cube when α is close to or equal to zero.

TABLE 1. Slant range (yd) for which assumption of usual toss bombing equation will result in 100-ft horizontal error ($K = 3$).

Airspeed (knots)	Dive angle (degrees)						
	0	10	20	30	40	50	60
250	1,160	1,340	1,420	1,570	1,780	2,100	2,570
300	1,480	1,730	1,860	2,050	2,340	2,770	3,380
350	1,830	2,150	2,330	2,570	2,950	3,300	4,260
400	2,180	2,580	2,830	3,140	3,600	4,270	5,200
450	2,550	3,050	3,370	3,740	4,300	5,100	6,200

It may be advisable to point out that the source of error just discussed does not appear to be a serious one. Frequently, release will be made at ranges considerably less than the values appearing in Table 1 and, because of the third or fourth power law, the horizontal error resulting will, accordingly, be markedly less than the 100 ft taken for the purposes of illustration. Furthermore, if this error is regarded as arising from an incorrect value of T_p, one can calculate [3,7] the percentage error in the value of T_p resulting from assuming a constant direction for the acceleration in deriving the expression for the correction factors of equation (6a). This suggests the desirability of modifying the form of the function ψ given by equation (6b) and illustrated in Figure 3. (ψ as used here is sometimes designated ψ' in the paper of London.[7]) Such a modified ψ, valid for pull-up angles less than 20 degrees, has been proposed [3,7] and is illustrated in Figure 4. It is apparent that these new ψ curves intersect at 17 degrees, instead of at 0 degrees, and that they exhibit less variation with T_c/V than did the unmodified curves.

THE EFFECT OF VARIABLE ACCELERATION DURING THE PULL-UP

A second possible source of error in the solution of the toss bombing problem is the assumption of a *constant* acceleration during the pull-up. The effect of a nonconstant acceleration has been considered in the report by London [7] and, for a horizontal approach, in an earlier paper by McLean.[2] Types of acceleration curves which have been experienced [3,7] are (1) acceleration increasing linearly with time, (2) acceleration increasing linearly until a definite value is reached, after which it remains constant, (3) acceleration increasing linearly, first at one rate and then at another, and (4) a linear increase followed by an actual decrease of the acceleration after a definite value has been attained. For the general case, the function $K + \sqrt{K(K-1)}$ which appears as an integrand in equation (4) (and in the analogous formula for nonhorizontal approaches) should be replaced [2] by the function

$$f(K) = K + \frac{K\int_0^t (K-1)dt}{\sqrt{\left(\int_0^t (K-1)dt\right)^2 + 2\int_0^t dt \int_0^t (K-1)dt}}. \tag{7}$$

Using this function, the general toss bombing equation will be [see equation (6a)]:

$$T_c = \frac{1}{\psi}\int_0^{T_p} f(K)dt. \tag{8}$$

If K is constant, the expression for $f(K)$ reduces to $K + \sqrt{K(K-1)}$. If, instead, K varies linearly with time, the correct function is

$$f(K) = K\left[1 + \sqrt{\frac{3(K-1)}{3K+1}}\right]. \tag{9}$$

The expression given in equation (9) has values commonly a few per cent less than the more common function $K + \sqrt{K(K-1)}$ and, as a result, the values of T_p derived by the use of the simple function as integrand would be expected to be a few per cent too small. Actually integrators which have been constructed use in effect a function.

$$\begin{aligned} f(K) &= \psi \quad \text{for } K \leqslant 1.3 \qquad (10)\\ f(K) &= K + \sqrt{K(K-1)} \quad \text{for } K > 1.3, \end{aligned}$$

so a linearly increasing acceleration, for which equation (9) should be used, is, in fact, quite accurately integrated by such integrators (see, for example, Figure 9 in reference 7). Similarly such integrators introduce only negligible errors of the order of 1 per cent when the other types of acceleration functions are involved.[7] It should certainly suffice to consider in this connection only values of K no greater than 6 and probably values of dK/dt no greater than 6 per sec.

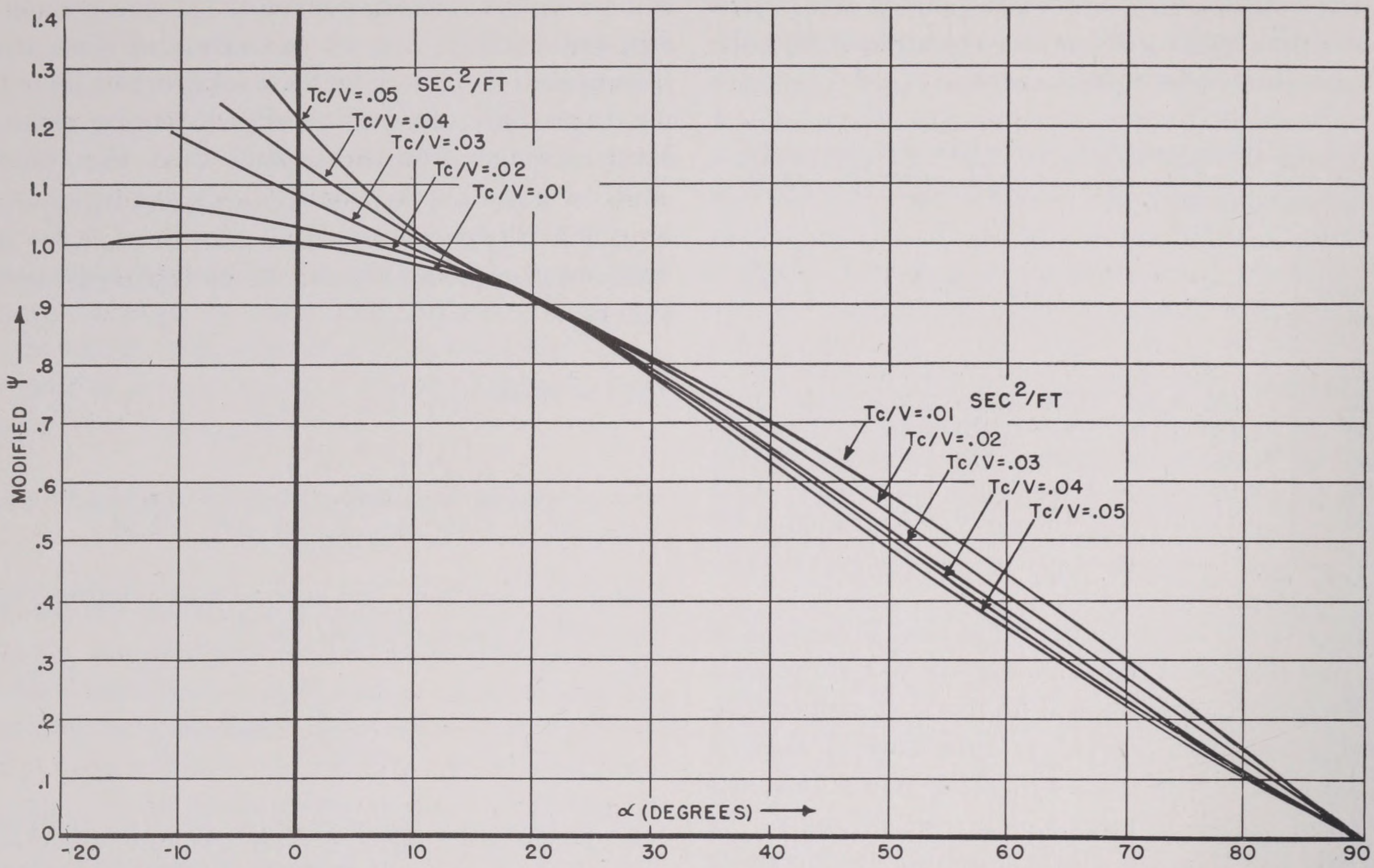


FIGURE 4. Plot showing the modified ψ function of α for various values of T_c/V. The modification is intended to compensate T_p for the effect of pull-up. ($K = 3$).

12.1.4 Examination of Additional Possible Sources of Error in Toss Bombing

EFFECT OF A SIGHT NOT ALIGNED WITH THE LINE OF FLIGHT

The effect of making an approach in which the flight path before pull-up is not a collision course with the target has been investigated.[4, 8] The results of this situation, which might arise through the use of a gunsight not exactly aligned with the line of flight, may be expressed in terms of the necessary compensation which could be introduced into the timing circuits. The percentage change required in the integrator ratio is roughly the same as the percentage which the sight offset is of the pull-up angle,[4] which, in turn, depends on the range at which the pull-up is initiated. More accurate relationships are given in curves and formulas in the latter more comprehensive reference.[8]

EFFECTS RESULTING FROM ATTACKING ON A PURSUIT COURSE

As a final point, it might be mentioned that in working papers of the Columbia University Applied Mathematics Group [56–59] an analysis has been made of the effect of an attacking aircraft making a *pursuit* attack on a target in motion (more accurately, on a target *in motion with respect to the air mass*). In these papers the case considered specifically is that in which an optical sight can be depressed by the proper "lead" angle (with respect to the datum line of the aircraft) so that the bombs may be released at the instant in the pull-up when the target flashes through the sights. The use of such sights presents, of course, obvious physical and physiological difficulties. However, from the analysis it appears that there is an opportunity for some compensating factors to enter. Thus, for a target motion directly away from (or toward) the attacking aircraft, the latter will experience an upward (or downward) acceleration as it proceeds along its pursuit course; as a result the dive angle, if measured by a pendulum device, will be in error. If this angle is taken in combination with the altitude to give a measure of the target range, the result will be the introduction of an excess lead not only in the proper sense to allow for the target motion but, at large dive angles, of about the proper magnitude.[58] Likewise, when following a target moving in azimuth, it is found that again there are some compensatory effects introduced. This is by virtue of the fact that the aircraft is obliged to bank in following the pursuit course and, in consequence, the lead (which is introduced in the plane of the *aircraft's* vertical) will place the sight not only above but also to one side of the moving target.

12.2 INSTRUMENTATION

From the previous discussion it is evident that, aside from the aiming of the aircraft (which is done visually), the solution of the toss bombing problem essentially requires the measurement of two distinct quantities. These quantities are (1) the time to target, T_c and (2) the time integral, from the start of the pull-up, of some function of the upward acceleration with proper dive angle compensation [see equation (8)]. In the simplest case these quantities might be regarded independently, in the sense that the value of T_c at which the pull-up should be commenced would be assigned in advance. Equipment would then be required to indicate to the pilot when the pull-up should be begun, and to release the bomb when the acceleration integral attained the correct value for the specified T_c. A more flexible and convenient arrangement, however, would be one in which the pull-up could be begun at the discretion of the pilot, and the value of T_c for that moment compared with the acceleration integral.

12.2.1 The Acceleration Integrator

Acceleration integrators for obtaining the integral of a suitable function of the upward acceleration have been the subject of considerable developmental work by the National Bureau of Standards under NDRC auspices. Such devices could be constructed mechanically, for example, by using the extra weight which will result from an upward acceleration to impart a torque and angular acceleration to a disk; when a suitable angular speed (which is the time integral of the angular acceleration) is built up, centrifugal force or other effects can be used to actuate the bomb release mechanism. Likewise, electrical methods — which may be more convenient — have been evolved in which the extra weight resulting from the acceleration is used to control the position of a slider on a variable resistor. The charging rate of an electric condenser can thus be made a suitable function of the upward acceleration and, if the time constant of the charging circuit is made sufficiently long, the voltage to which the condenser is charged will be at every instant very close to an accurate measure of the required acceleration integral. Since the applicability of radar range information to the toss bombing problem is neither to the acceleration integrators nor to the devices for measuring the dive angle α we shall, in what follows, confine our attention to the measurement of T_c and to those cases in which the value of T_c is intimately incorporated into the acceleration equipment.

12.2.2 Nonradar Methods of Determining T_c

Since the time-to-target, T_c, depends not only on the range to the target but also on the relative rate of approach and is, in fact, equal to the ratio of these quantities, it is evident that something more than a mere estimate of range by stadiametric or other methods will be required. It is also evident that the rate of closure cannot be obtained satisfactorily from the airspeed of the attacker, since for a ground target, the effect of wind would then introduce an error, and for an airborne target, a precise estimate of target speed would be required. In the following paragraphs nonradar means of obviating these difficulties will be described and it will be seen that these methods possess the further advantage of not requiring a knowledge of the physical size of the target. It will be seen subsequently that these methods have their radar analogues, so they are presented for this reason as well as for completeness.

Optical Methods

In one optical method for determining T_c use is made of a clock mechanism which can be started and reversed at will. If such a clock is started at the instant when a target subtends some given angle in an optical sight and is reversed when the subtended angle has doubled, it is clear that at the moment at which collision with the target would occur the clock would have returned to zero. The clock reading will, therefore, represent, at every instant after its reversal, the time remaining before the impending collision. It has further been pointed out [91] that the ratio of the angles subtended at the times the clock is started and reversed may be something other than 1 to 2 if a clock is provided which runs at different speeds forward and backward. Essentially what is being done, of course, is to obtain a measure of T_c by timing an interval during which the distance from the target changes by a certain *ratio;* following such a measurement an up-to-date value of this quantity is provided by continuously subtracting the time which elapses thereafter.

By such a device we have an ingenious means of providing the acceleration integrator with the quantity T_c which it needs to release the bombs at the proper instant. It is clear, furthermore, that this method does not require a knowledge of the dimensions of the target. In its practical application to airborne targets in particular, this method has, however, certain disadvantages connected with the fact that at long ranges stadiametric measurements on small targets may suffer from loss of accuracy, while possible measurements based on the entire width of a bomber formation may be invalidated by changes in the physical dimensions of the formation during the course of attack.

BAROMETRIC METHODS

A method of determining T_c which has some similarity to the use of the reversible clock is one involving the use of a pressure altimeter in a straight line diving approach. In such an approach the relative change in the altitude differential between the attacking aircraft and the target is identical to the relative change in range to the target. Thus the time interval during which the altitude above the target changes by a definite fraction of its initial value will serve as a measure of the time T_c remaining before the impending collision. Specifically, for example, if the time taken to dive from one altitude to another five-sixths as great is measured, the time T_c remaining will be five times this time interval. More generally, equation (8) could then be rewritten in terms of such a time interval in the following form

$$\frac{1}{(h_1/h_2) - 1} \cdot t_{12} = \frac{1}{\psi}\int_0^{T_p} f(K)dt. \qquad (11)$$

Here, of course, h_1 and h_2 are the altitudes above the target at the beginning and end of the time interval t_{12} being measured and the pull-up is presumed to start immediately thereafter. (Strictly what is required is that the *acceleration integrator* be started functioning immediately at the end of the interval measured, in order that the value of T_c so determined be used correctly.)

The method just described has seen extensive use in flight tests, and has made use of a "multiple point" Kollsman aneroid altimeter in which contacts are spaced around the rim of the altimeter face at positions such that the successive altitudes corresponding to these positions have the 5:6 ratio mentioned above.[19] A complete system employing such a device will be described in somewhat greater detail below but it might be appropriate first to point out here certain limitations which are inherent in this method aside from purely instrumental difficulties connected with data take-off problems and possible sluggishness in the barometric element. One fundamental limitation to the use of altitude variation for determination of T_c is its obvious uselessness in a horizontal approach, such as might best be employed against an airborne target. A difficulty which arises in a diving attack is the necessity for knowledge of the barometric altitude of the target. Conceivably, of course, this latter difficulty might be overcome by adjusting the barometric element while "buzzing" a region at the same altitude as the target or by comparing the barometric reading with that obtained from a radar altimeter while flying over the area in question. These considerations are mentioned not to disparage the use of a barometric device for toss bombing, but merely to indicate some of the problems which may in some cases limit its applicability. Barometric lag is strongly affected by the nature of the installation and can be a real difficulty with some types of airplanes (as, for example, in the P-38 with the present type of static tube installation).

BRIEF DESCRIPTION OF A TOSS BOMBING SYSTEM EMPLOYING A BAROMETRIC ELEMENT

As indicated above, toss bombing tests have been made using a multiple point barometric altimeter for the determination, essentially, of the quantity T_c. The other vital system elements are, of course, the acceleration integrator itself and the device which measures the dive angle, α, and provides the correction factor ψ. To illustrate how such a system[19] would work see Figure 5, in which charging circuits for two capacitors (C_1 and C_2) are shown. The voltages which will be built up on these two capacitors will serve respectively as measures of $\psi \cdot T_c$ and of the acceleration integral $\int f(K)dt$. The equality between these voltages will, in accordance with the basic equation (8), indicate the time at which the bomb should be dropped and can cause a thyratron (not shown) to actuate the bomb release mechanism.

In continuing with the analysis of the circuit shown in Figure 5, we shall assume for simplicity that the two capacitors shown are equal, each having a capacity C. The potentiometer R_α is intended to make available to the charging circuit R_1C_1 a voltage which is obtained by multiplying the supply voltage by the factor ψ, which represents the correction for dive angle. Accordingly the setting of the potentiometer R_α is controlled by the equipment for measuring dive angle (for example, a free vertical-erecting gyro) in such a way that the voltage obtained at the arm of the potentiometer is just $\psi \cdot V_0$. (Strictly, the value of ψ, which is primarily a function of α, and shows negligible dependence on K, exhibits some variation with T_c/V. How some allowances may be made for this fact will be indicated later.)

To indicate how the quantity T_c is introduced into the circuit, we now consider the action of the multiple point barometric element described previously. Use is made of this unit after the pilot has entered his dive, attained a reasonably constant airspeed, become lined up on the target, and has reached the altitude at which he wishes to begin the final stage of the attack. The pilot then closes a switch ("pickle switch") which is at his disposal with the result that, at the next contact made by the barometric element, switch S_1 is closed automatically and the capacitor C_1 begins charging. When the altitude has decreased to a point where a second contact is made by the altimeter, switch S_1 is again opened and switch S_2 is closed; the charging circuit for C_2 is thereby connected to the voltage source and the pilot is given the cue to pull out of his dive. We are left meanwhile with a charge stored on C_1, which, if linear charging can be assumed,[48b] results in a potential given by:

$$V_{C_1} = \frac{\psi \cdot V_0}{R_1 C} t_{12} \tag{12a}$$

$$= \frac{\psi \cdot V_0}{R_1 C}\left(\frac{h_1}{h_2} - 1\right) T_c. \tag{12b}$$

Note. The possibility of some nonlinearity in the charging circuit can be exploited [19] to make some allowance for the slight variation of ψ with T_c/V. If some value of V is taken as typical, an unusually large value of T_c would result in the nonlinearity of the charging circuit becoming particularly important and a somewhat reduced value of V_{C_1} being obtained. This effect is therefore in the same sense as would be obtained (for the usual values of α) by altering ψ in accordance with its dependence on T_c/V and evidently [19] satisfactory compensation can be obtained in this way. As a further remark it might be added that presumably the voltage divider represented by the potentiometer R_α is a device of sufficiently low impedance that variation in its setting will not result in a harmful variation of the total effective resistance in the circuit R_1C_1.

The closing of S_2 starts the process of charging the capacitor C_2 through the resistor R_2. This resistor is the heart of the acceleration integrator and its value will be dependent upon the amount of acceleration to which the aircraft is subjected. Again assuming linear charging, the potential built up on C_2 in a time t will be

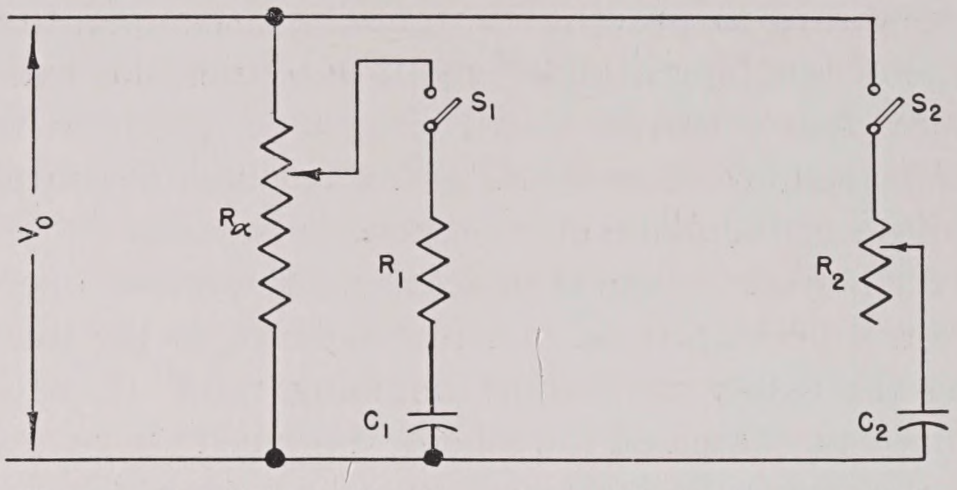


FIGURE 5. Schematic diagram to illustrate a possible toss bombing circuit.

$$V_{C_2} = \frac{V_0}{C}\int_0^t \frac{1}{R_2} dt. \tag{13}$$

The value R_2 of R_2 should be arranged to vary with K so that

$$R_2 = \frac{R}{f(K)}, \tag{14}$$

where R is a constant and $f(K)$ may be taken as $K + \sqrt{K(K-1)}$ or a suitable approximation thereto. We accordingly can express V_{C_2}, as given by equation (13), in the following form:

$$V_{C_2} = \frac{V_0}{RC}\int_0^t f(K) dt. \tag{15}$$

As stated above, the bomb release will occur when t has attained such a value that V_{C_2} has become equal to V_{C_1}; in order that this release satisfy equation (8), a comparison of equations (12b) and (15) shows that we should put

$$R_1 = R\left(\frac{h_1}{h_2} - 1\right). \tag{16}$$

In the particular case cited previously as an example, $h_1/h_2 = 6/5$, so the relation expressed by equation (16) would then become

$$R_1 = \frac{R}{5}. \tag{17}$$

After the bomb has been automatically released an indication of this fact is, of course, given to the pilot and he is free to take whatever evasive action he may wish. In addition to his responsibility for uncaging the gyro, which is used to measure the dive angle, and

[redacted]

taking care to prevent its tumbling thereafter, this type of bombing attack[98] requires of the pilot little more than a careful visual aim, some attention to the constancy of airspeed, and a reasonably abrupt pull-up in the plane of the aircraft's vertical.[56–59, 98] A further advantage is that the entire cycle of operation is accomplished in a few seconds, so the pilot has the safety of a short bombing run.[98] If, with equipment based on the scheme described above, the pilot releases the pickle switch after having closed it at some point during the dive, the operation of the equipment is stopped and the apparatus is ready for operation at a lower altitude. It is evident that variations and refinements of the circuit described are possible, but the above rudimentary material was presented in order to illustrate how the principles described earlier may be applied. One possible refinement, of course, would be a provision to compensate for the very slight deviation of the bomb trajectory from the theoretical path it would follow in the absence of air resistance. Such a correction may, to a first approximation, be applied by multiplying T_c by a factor slightly larger than unity which varies linearly with the range and in general is small enough that an average value of range can be used.

12.2.3 The Use of Radar in Toss Bombing

From the foregoing discussion of possible nonradar means of instrumenting a toss bombing attack, it is immediately evident that radar range could be introduced into the technique in a quite straightforward manner and with possible advantages from the point of view of convenience or accuracy. Other more subtle and intimate means of introducing radar range have also been proposed, but in what follows, we shall consider first the radar methods analogous to the nonradar schemes already described and will begin with the use of radar altitude.

The Use of Radar Altitude

From the discussion of barometric methods in Section 12.2.2, it was noted that such methods may be handicapped by the lack of information concerning the barometric altitude of the target and conceivably could suffer from possible sluggishness in the equipment. It is natural to inquire, therefore, whether a radar measurement of the height above the terrain would not be more suitable.

One method of obtaining and using such radar altitude information would employ an *airborne range only* [ARO] equipment such as the AN/APG-5 (see Section 20.3),[22] although the use of microwave frequencies is by no means essential. (It might be desirable in using AN/APG-5 equipment for this purpose to provide an antenna mounted in a different fashion from that customary in fire-control applications.[22]) The use of ARO could be quite analogous to the use of a barometric element, since the servo unit designed as an adjunct to the ARO automatically provides range as a shaft rotation, and a set of contacts could be provided to function in the same way as those on the pressure altimeter. The ARO equipment, primarily designed for ranging on other aircraft, normally provides the range to the *nearest* target in its fairly broad field-of-view and there should be no difficulty in obtaining the range to the closest point on the earth's surface if the range covered by the servo unit were made adequately great.

It will be immediately recognized, however, that an approach over rough terrain would make radar altitude information completely useless for the purpose considered here. In fact, even over water or relatively smooth terrain there will be some fluctuations in the output[22] which, from the standpoint of accuracy, would set a practical lower limit to the difference of the altitudes h_1 and h_2 between which measurements are made. Thus even under favorable conditions, the time required to determine T_c with suitable accuracy might be about 3 sec and it could scarcely be claimed that the use of radar would permit a virtually instantaneous determination of this important quantity. Effects of this nature, which will be discussed in further detail in the following subsection, suggest a reason why there would be less benefit than one might expect in attempting to differentiate the altitude reading and provide T_c essentially by furnishing instantaneously both the altitude, h, and its derivative, dh/dt. In the summer of 1945, tests with ARO radar equipment replacing the barometric altimeter were being seriously considered by personnel of the Army Air Forces Proving Ground Command (Eglin Field).

In both the barometric and the radar methods for the determination of T_c by altitude measurements, arrangements might be contrived for commencing the measurement procedure the moment the pickle switch is pressed, without waiting until the next one of a discrete number of contacts is reached. With our attention now directed towards the application of radar to the toss bombing problem it would seem inappropriate, however, to discuss this particular point in connection with the use of radar altitude, since our interest in this particular method is rather considerably reduced by the difficulties which perforce arise in operations over rough terrain. It might further be pointed out that, just as with the barometric altimeter, the use of radar altitude will not permit a determination of T_c to be made in the case of a *level* approach, such as might be used against an airborne target.

The Direct Use of Radar Range Measurements to the Target Itself

In considering the use of radar range to the target itself as an aid in solving the toss bombing problem, ARO equipment again might appear suitable. Since the radar beam from the antenna of such equipment in its standard form is fairly broad (width to half-power points, 28 degrees), there would be little danger of losing the target in making a leading attack. It would be admittedly a difficult problem to use such equipment for direct ranging against a target on the ground, but attention is directed to the existence of somewhat more complicated equipment like Vulture (AN/APG-13B) and Terry (AN/APG-21), designed to measure range to such targets for fire-control applications (see Sections 20.5 and 20.6). The adaptation of Terry equipment to this application would appear in fact to be a potential means of *increasing its usefulness as a universal fighter radar*. If direct range measurements are desired to an isolated target on the surface of the water, it should be possible to modify the ARO equipment so that it will measure the target range instead of the altitude signal, which is a signal necessarily at a closer range than the target itself. In an attack against an airborne target, however, the range to the target will sometimes be greater than and in other cases less than the altitude and, in fact, may pass from the first of these conditions to the second during the interval in which T_c could be measured. Under such circumstances, therefore, it would be desirable to shield the radar antenna in such a way that no altitude signal would be received; this should be possible in general, although a careful installation study would be required for each type of airplane involved.

The range at which present ARO radar equipment, *if operating at peak performance*, can obtain a signal of adequate strength from even a single bomber-type aircraft should be sufficient (at least 3,000 yd), for toss bombing purposes. Adequate range performance certainly can be expected from surface-vessel targets. By methods analogous to those discussed in Section 12.2.2, range data derived from the shaft of the ARO servo unit could then be readily used to measure the time interval during which the target range changes by a definite fractional amount and so serve, essentially, to provide a measure of T_c. It would seem reasonable, however, to consider means for avoiding the use of the servo unit mentioned above. Since the ARO range unit contains automatic range-tracking circuits which provide a voltage varying in a precise linear manner with the range of the target, the servo unit does no more than convert this voltage into a shaft rotation. The elimination of the servo unit would, of course, necessitate the manufacture of an additional electronic unit to make use of the range voltage output from the ARO, but would have the advantage of avoiding possible sluggishness in a mechanical unit such as the servo. (The speed of response of the servo would perhaps only be important in the first stages of getting onto the target, but this aspect might be a real difficulty in a toss bombing attack, in which very little time is available. Actually, the production servos were capable of speeds greater than 500 yd per sec on the 2,000-yd scale.) By voltage-comparison circuits,[47a] the range unit voltage can be used to control circuits or mechanisms which will, as before, measure the time interval between any two desired ranges. The use of such methods was once considered for the adaptation of the longer wave AN/APS-16 tail-warning equipment to toss bombing.

The Use of Radar Range and Range-Rate in Toss Bombing

As was pointed out in Section 12.1.2, the quantity T_c is at every instant equal to the range to the target divided by the rate of closure. It would therefore appear reasonable to inquire whether a measurement of range rate could not be obtained and applied to the solution of the toss bombing problem. The frequency shift which, by virtue of the doppler effect, is experienced whenever a target is in motion with respect to the radar could possibly be exploited to measure range-rates for toss bombing applications. In point of fact, in the design of the Sniffer equipment mentioned briefly in one of the introductory paragraphs of this chapter, the doppler effect has been used to provide range-rate information but essentially in a *linear* combination with range. The possible usefulness of AN/APG-22 or AN/APG-24 equipment, also referred to earlier, should not be overlooked. In what follows, however, we shall consider exclusively the use of range rates obtained by the differentiation of range voltages, such as are obtainable conveniently with pulsed radar equipment like the ARO. It should perhaps be pointed out in advance that the derivation of such range rates may not mean that a determination of T_c can be made *instantly*, since the rates obtained may require a certain amount of smoothing which would in turn require that a certain time elapse before an accurate rate can be considered established. When this aspect of the problem is considered it appears that, aside from possible convenience or elegance in the instrumentation, there may be little fundamental advantage to be obtained in practice from the explicit use of range rates in toss bombing instead of the "two point" methods considered previously.

Differentiation of a range voltage to obtain a range rate may be achieved in a very approximate manner by a measurement of the voltage drop across the resistor of a series resistance-capacity circuit although more involved circuits of suitable accuracy have been constructed for the purpose.[48c] Once obtained, a voltage representing the rate of closure may be employed in a variety of ways in the solution of the toss bombing problem. In order to avoid the inconvenience of instrumenting a direct division [48d] of range by range-rate to obtain T_c, it is expedient to contrive methods for which this division will be unnecessary.

A particularly straightforward use of voltages representing range and range-rate can be made if a particular value of T_c at pull-up is chosen in advance. In such a case the voltages representing these factors, with suitable proportionality constants, can be compared in a differential amplifier circuit,[47a] for example, and, when the range has decreased to a value equal to the assigned T_c times the rate, a relay in the plate circuit will be actuated to start the acceleration integrator and give the cue to the pilot to begin the pull-up. The factor ψ for dive-angle compensation could

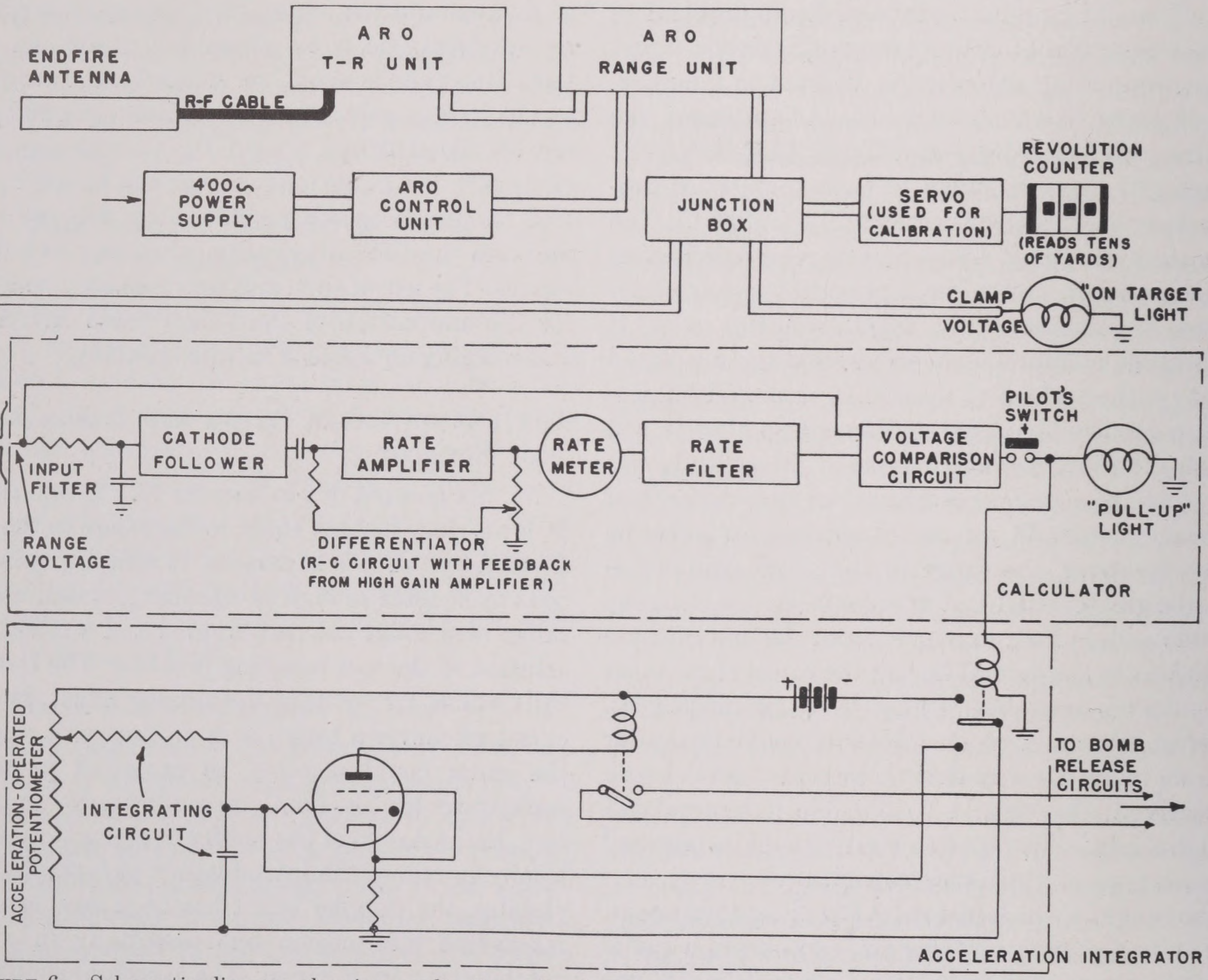

ENDFIRE ANTENNA
R-F CABLE
ARO T-R UNIT
ARO RANGE UNIT
400∿ POWER SUPPLY
ARO CONTROL UNIT
JUNCTION BOX
SERVO (USED FOR CALIBRATION)
REVOLUTION COUNTER
(READS TENS OF YARDS)
CLAMP
VOLTAGE
"ON TARGET" LIGHT
PILOT'S SWITCH
INPUT FILTER
RANGE VOLTAGE
CATHODE FOLLOWER
RATE AMPLIFIER
RATE METER
RATE FILTER
VOLTAGE COMPARISON CIRCUIT
"PULL-UP" LIGHT
DIFFERENTIATOR
(R-C CIRCUIT WITH FEEDBACK FROM HIGH GAIN AMPLIFIER)
CALCULATOR
ACCELERATION-OPERATED POTENTIOMETER
INTEGRATING CIRCUIT
+
-
TO BOMB RELEASE CIRCUITS
ACCELERATION INTEGRATOR

FIGURE 6. Schematic diagram showing application of radar range and range-rate to toss bombing. The use of ARO equipment is indicated in combination with a circuit for obtaining range-rate and an early acceleration integrator (controls for adjustment not shown).

presumably be introduced by use of a potentiometer in the range voltage channel of the circuit; furthermore, the value of T_c used can be readily selected by means of a potentiometer in the rate circuit if a suitable adjustment of the acceleration integrator is made concurrently. A circuit of this type, without dive angle compensation, was constructed and used in conjunction with an early ARO equipment for toss bombing tests at the Army Air Forces Proving Ground in the spring and early summer of 1943. A block diagram of this system is shown in Figure 6 in combination with an early acceleration integrator. (The circuit of this "calculator" is given in Dwg. A14995-A of the Radiation Laboratory, Massachusetts Institute of Technology, and a block diagram of the entire system in Dwg. A14994-A. Some remarks on its performance will be made under Section 12.3.2.) Many variations of the detailed means by which range-rate can be applied to toss bombing will, no doubt, occur to our readers, but it might be of interest to present in the following paragraph one other method which has some unique features.

An interesting type of toss bombing device which has been designed in laboratory form (again without dive-angle compensation) varies the quantity to be integrated by the acceleration integrator in direct proportion to the range-rate. A voltage comparison circuit then effects the release of the bomb when the integrator output becomes equal to the range voltage. The circuit of this calculator is shown in Figure 7. It is evident that such an arrangement permits the pilot to begin his pull-up at any time he may choose, provided only that the radar is given sufficient time to establish accurately the range and (more particularly) range-rate voltages. It might be noted, however, that the usual toss bombing equation will require modification if up-to-date range data are used during the pull-up, since the relationships developed previously were based on the supposition that T_c would be determined at a moment prior to the pull-up and the integrator would allow for the subsequent forward motion. A final practical point which should not be overlooked is that with such a device one must insure the continued reception of a radar signal from the target throughout the pull-up until the moment of bomb release; this may in some cases prove a requirement difficult to meet if it is also required that no altitude signal be received during level flight.

12.3 RESULTS

Toss bombing tests in which radar data were used are neither so numerous nor so recent as are nonradar tests of this technique. In the following sections no attempt will be made to digest the results of all toss bombing tests made to date, but a brief indication will be given of the accuracies which can be expected at the present time. It should be noted in passing that toss bombing requires quite accurate timing on the part of the equipment — and, by the same token, on the part of test equipment for calibration — since the total time consumed in measuring T_c amounts usually only to a few seconds and the pull-up time before bomb release is typically little more than one second.

12.3.1 Nonradar Toss Bombing Tests

It is sometimes convenient, of course, to be able to test separately the various components of a bombing system and this can be done to some extent in toss bombing through the use of markers on the ground, stop watch or theodolite methods, and the like. The greater part of the testing, however, appears to have been done directly by actually observing drops made with practice bombs.

One series of toss bombing tests carried out by the U. S. Navy involved drops from three SB2C and one F6F aircraft at slant ranges varying from 11,200 to 4,100 ft.[96] In this series of runs, diving attacks were made against markers on the surface of the water and a multiple-point pressure altimeter served to measure T_c. The results quoted showed an average *range* error of 86½ ft attributable to inherent equipment error and pilot sighting. It was recommended that until a drift-computing sight should be developed, "the practice of diving with or against wind and/or target motion be employed to make deflection correction easier, aiming off to compensate for drift." The limitations of a radar altimeter were also indicated.

It is interesting to note that, in an earlier series of over-water toss bombing tests made in connection with this project,[95] use was made of an AN/APN-1 type (AYF) radar altimeter. Preliminary tests with this method of timing resulted in an average range error of 45 ft and led to the recommendation that "encouragement be given to development of AIBR (Acceleration Integrator Bomb Release) combined with the AN/APG-4 (Sniffer)." It is understood that further tests showed difficulties attributable to time lags and other inaccuracies of the AYF altimeter.

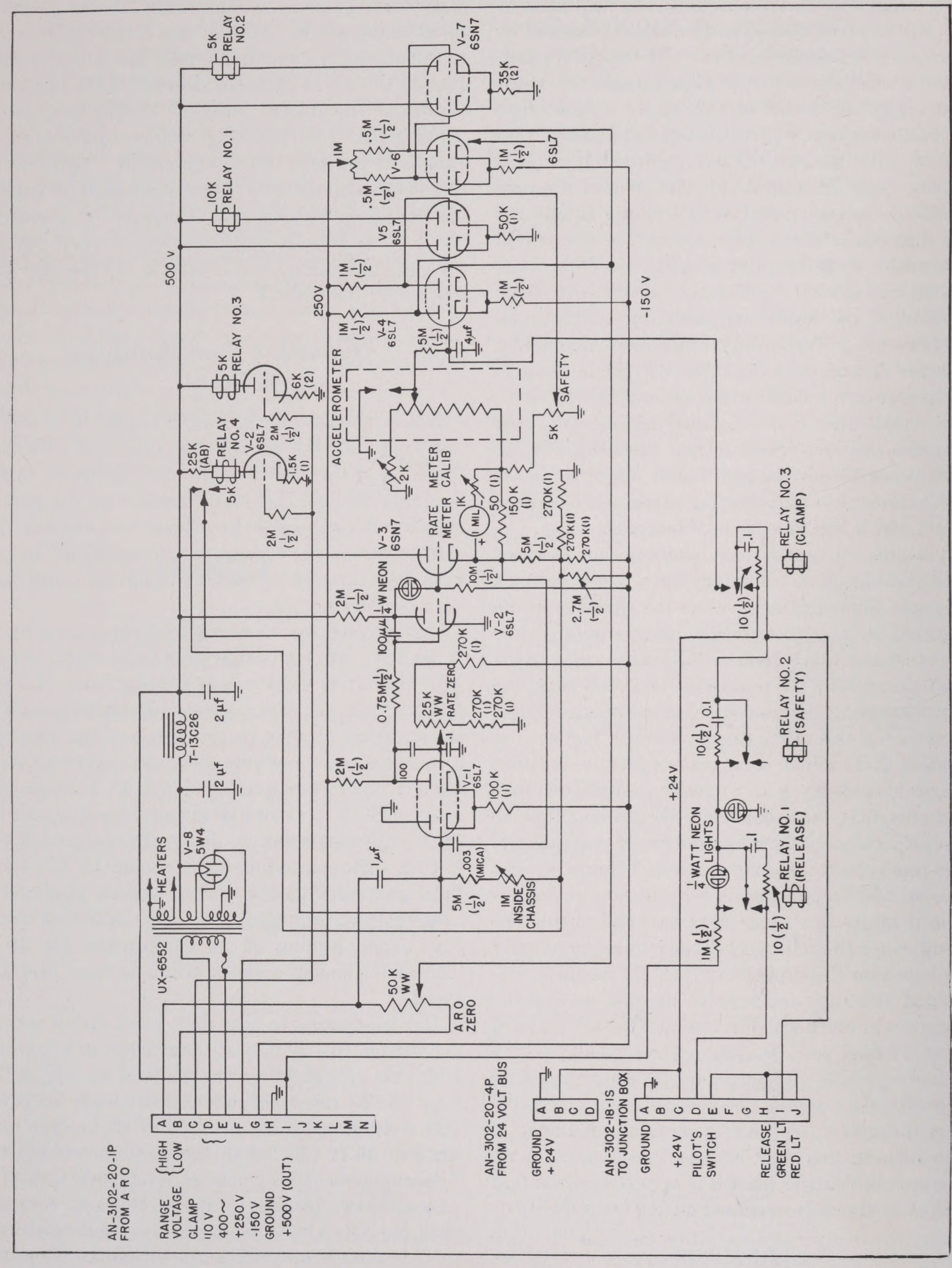

AN-3102-20-1P
FROM A R O
RANGE VOLTAGE {HIGH {LOW
CLAMP
110 V
400~
+250 V
-150 V
GROUND
+500 V (OUT)
A B C D E F G H I J K L M N
AN-3102-20-4P
FROM 24 VOLT BUS
GROUND
+24 V
A B C D
AN-3102-18-1S
TO JUNCTION BOX
GROUND
+24V
PILOT'S SWITCH
RELEASE
GREEN LT
RED LT
A B C D E F G H I J
UX-6552
HEATERS
V-8
5W4
T-13C26
2 μf
2 μf
500 V
250V
-150 V
+24V
5K RELAY NO.2
10K RELAY NO.1
5K RELAY NO.3
25K (AB)
5K
RELAY NO.4
V-2 6SL7
2M (1/2)
1.5K (1)
6K (2)
2M (1/2)
V-7 6SN7
35K (2)
V-6
.5M (1/2)
.5M (1/2)
1M
1M (1/2)
6SL7
V5 6SL7
50K (1)
1M (1/2)
1M (1/2)
1M (1/2)
V-4 6SL7
5M (1/2)
4μf
ACCELEROMETER
SAFETY
5K
2K
METER CALIB
RATE METER
V-3 6SN7
1K
1 MIL
50 (1)
150 K (1)
270K (1)
5M (1/2)
270 K(1)
270 K(1)
2.7M (1/2)
10M (1/2)
2M (1/2)
1/4 W NEON
100μμf
V-2 6SL7
270K (1)
0.75M(1/2)
25 K WW RATE ZERO
270K (1)
270K (1)
2M (1/2)
100
.1
V-1 6SL7
100 K (1)
1μf
.003 (MICA)
5M (1/2)
1M INSIDE CHASSIS
50 K WW
A R O ZERO
RELAY NO.3 (CLAMP)
10 (1/2)
.1
RELAY NO.2 (SAFETY)
10 (1/2)
0.1
1/4 WATT NEON LIGHTS
.1
RELAY NO.1 (RELEASE)
1M (1/2)
10 (1/2)

FIGURE 7. Electric acceleration integrator and release computer.

More recently an overall test of the AN/ASG-10 (XN) equipment, consisting of acceleration integrator equipment based on designs of Division 4 of NDRC and a Kollsman pressure-type altimeter, was made in an F4U airplane.[97] Specifically the equipment comprised (1) a computer, Mk 20, Mod. 0; (2) an altimeter, Mk 1, Mod. 00; (3) a dive angle gyro, Mk 20, Mod. 0; (4) a control box; and (5) an indicator light. A stationary water target was used and attacks were run with a 40-degree dive angle, an indicated airspeed of 340 knots, and release at a slant range in the neighborhood of 7,500 ft or, in some runs, of 5,000 ft. The average *radial* error for the bomb drops made in the course of these tests was 152 feet. The AN/ASG-10 equipment can also be used for rocket launching.

The report [97] of the tests mentioned above points out that the "AN/ASG-10 equipment does not compensate for wind effects and the pilot must make the proper allowance in his sighting." The report states further that "in these tests the pilots . . . calculated the point of aim from the best upper wind data available and made their first runs using this point of aim. They then adjusted the point of aim for subsequent bombs to bring them on the target. Tests were not made on a moving target because no suitable target boat was available during the period of these tests." It might be added that the wind speeds averaged about 25 mph and that runs were made up wind, down wind, and cross wind. As a second point, it was found that an adjustable sight is desirable, if it is to be usable for gunfire and for conventional dive bombing as well, since the sight should be set about 30 mils above the boresight datum line when making a 40-degree dive at 350 knots. Finally, it might be noted that, for the installation used in these tests, the suspected lag of the pressure altimeter was "small and can be disregarded." Additional tests are described in a report from Williams Field.[87]

12.3.2 Tests of Toss Bombing Methods Employing Radar

General

Various methods of employing radar ranging in the solution of the toss bombing problem have been mentioned previously in this chapter but, in what follows, we shall refer in particular to the series of tests run at the Army Air Forces Proving Ground (Eglin Field) during the spring and summer of 1943. In these tests use was made of an early ARO equipment plus a calculator unit, which employed range rate in the determination of T_c and was constructed along the lines indicated in "The Use of Radar Range and Range-Rate in Toss Bombing," Section 12.2.3 and Figure 6. Also, one of two Bureau of Standards acceleration integrators (without dive-angle compensation) could be selected for use with this radar equipment. These units were mounted in a B-25D airplane for the purpose of the tests.

Tactical Use Visualized

The primary tactical use which was foreseen for the toss bombing technique at the time of the Eglin tests was for air-to-air work, in which a fighter plane (such as a P-38) or a fast attack bomber (such as an A-26) would make a toss bombing attack on a formation of hostile bombers in the hope of breaking up the formation and making it more susceptible to conventional fighter action. A direct hit on a member of the bomb formation was not considered necessary, since proximity fuses could be used.

Features of Tests

Despite the greater importance which was attached to air-to-air work at that time, many tests were made against ship silhouettes in order to test the equipment and the method more conveniently. It will be recalled that before the advent of Terry equipment the use of radar in toss bombing appeared to be most suitable for airborne targets, which are attacked without diving, or against targets on the surface of the water. The B-25 airplane was scarcely capable of as rapid rates of climb as would be desired in combat, but it served nicely for the purpose of the tests. Because of the early form of the equipment and the experimental nature of the tests, an operator rode in the nose with the radar units and insured that the proper signals were received. In the runs against water targets, as well as in the air-to-air work, the attempt was made to approach at an altitude as close as possible to that of the target, since no dive angle compensation was then available.

Some Difficulties Encountered

It was found early in the tests that although the ARO equipment presumably gave quite accurate range voltages, rates obtained from these voltages by differentiation showed rather large and rapid fluctuation. Very roughly, the fluctuations experienced might be judged to have a period of the order of a second and some filtering was clearly essential in order that an accurate measure of T_c be obtainable.

It was, on the other hand, of real importance to avoid introducing a filter with a slow transient response, for then an excessive time would be required to establish an accurate rate at the output of the filter. A reasonable compromise in filter design resulted in a three-stage rate filter which had considerable attenuation for frequencies of the order of 1 c but which would respond to a step function almost completely (within 3 per cent) in 3 sec. (To reduce somewhat the time required to establish the correct rate voltage at the output of the filter it was suggested that the filter be charged to some intermediate value until a radar signal is obtained from the target and range tracking begins. However, such obstacles as electrical leakage in certain relay contacts introduced difficulties in the exploitation of this idea in the tests being discussed and full use was not made of the suggestion.) With such a filter it then became necessary that radar data be obtained for at least 3 sec prior to the pull-up time in order that an accurate determination of this instant be obtainable.

In the B-25 installation the altitude signal received by the radar was not found to be strong, although no great pains had been taken in mounting the antenna to avoid it. It was, however, necessary for the operator to guard against the occasional possibility that the range tracking circuits would lock onto the altitude return instead of the signal from the target. In air-to-air tests a radio-controlled drone (PQ-8) was used as a target, sometimes flanked by one or two other small aircraft. Because of the low radar cross section of such targets — plus the fact that there was no AFC nor, at that time, exceptional stability in the r-f circuits — it was desirable for the operator to check the tuning occasionally in the course of flight.

With some improvement in these design features of the radar equipment and with the larger cross sections presented by bomber type of aircraft, there is perhaps no essential difficulty with respect to maximum range. If, then, the altitude signal were eliminated, it would appear entirely possible for the radar to feed data to the other equipment and to the pilot with no attention from an operator. In brief, the radar would search in range until picking up the target, at which time the so-called clamp voltage would cause automatically an on-target light to come on and range information would be made available to the calculator. Then, when the range decreased to such a value that it equaled the assigned T_c times the range-rate, the integrator would start, as before, and the pull-up light give the cue to the pilot.

ACCURACY

In tests against water targets with the equipment described above, an average range error of 30 ft is quoted. The tests were made with values of T_c of 7 or, occasionally, 9 sec. In the work against airborne targets the range errors were roughly three times as great and it was estimated that the average *vertical* error was approximately 30 ft.

Such accuracies were felt to be definitely encouraging, particularly in view of the rudimentary nature of the equipment used. It was recognized, however, that many engineering and production problems would require solution before combat use could be made of equipment of this nature. The indiscreetness of introducing such a technique at a time when the Allied bombing effort was on the increase led to discouragement of a future program for air-to-air toss bombing. For air-to-air work particularly, radar range data can certainly be of value and methods such as those discussed in Section 12.2.3 would appear to warrant careful consideration for this purpose.

Chapter 13

RADAR BOMBING ASSESSMENT AND TRAINING

In the previous chapters of Part II, the necessity of providing highly skilled operators for airborne radar bombing systems was stressed many times. The desired degree of operator skill is developed only as the result of much training and experience over a period of many months. In order to reduce the training time and to lighten the operator's task, the trend of bombing computer design is toward the more complex mechanisms that function almost automatically. Although this policy succeeds in reducing the amount of operator training required, it results in a compensating increase of emphasis in training maintenance personnel. It thus becomes apparent that training, in one guise or another, will always play a major role in scientific warfare.

First, the problem of bomb scoring and assessment will be considered. This includes all methods of determining the accuracy with which bombs are dropped, both in operational use and in training programs.

13.1 BOMB SCORING AND ASSESSMENT

13.1.1 Introduction

There are three general methods of determining the accuracy of bombing systems. The first of these is the dropping of practice bombs and observing their point of impact. Over the ocean or on bombing ranges this is generally a very satisfactory procedure. Of course, if damaged bombs are employed, this may not be the case. However, in training operators how to bomb complex industrial targets, the use of practice bombs would most certainly have severe repercussions. To avoid this, optical and radar pseudo-bombing schemes were devised. In these schemes, the impact point is determined from the velocity of the aircraft and the bomb characteristics, once the release point has been established.

In developing a system for assessing bombing results without dropping bombs, a number of requirements of different relative importance have to be met. A list of typical requirements follows.

1. Accurate determination of the impact point (within ± 10 mils if possible).
2. Operation over a large range of altitude, e.g., from 100 to 35,000 ft.
3. Independence of weather conditions.
4. Ease of operation.
5. Simplicity of equipment construction.
6. Ability to handle large numbers of planes in a short time.
7. Portability of equipment.

Of these requirements, the first is the most important. It should be noted, however, that just as a micrometer is not used to measure the lumber in constructing a house, the necessary accuracy of a bomb scoring system depends on the accuracy of bombing systems being assessed.

13.1.2 Optical Photoscoring Methods

There are two possibilities for optical bomb scoring, namely, photography from the airplane being scored and photography from the ground (phototheodolite). Of these, the latter is unquestionably more accurate, but it is restricted to only one target at a time and presents greater ground-air liaison problems. On the other hand, the method employing a vertical camera in the aircraft is not restricted to any particular target, but appreciable errors are introduced if the camera is not exactly leveled. Obviously, both methods are subject to visibility restrictions.

AIRCRAFT CAMERA METHOD

The aircraft camera method is described in a report of the Department of Training and Operations of the Victorville Army Air Field.[72] A series of vertical aerial photographs are taken on the bomb run, and the camera is so arranged that a watch with a sweep second hand is photographed at the same time. The camera must be accurately leveled and oriented with respect to the longitudinal axis of the airplane. Type K8AB, K-21, and K-22 cameras can all be used for this purpose.

The method was initially devised for scoring operators using the semisynchronous, radar-Norden bombsight tie-in (see Section 8.3.1). In this case, the bombardier takes pictures at five points on the bombing runs, namely, (1) at the final radar check point, (2) at the bomb release point, (3) at a point approximately midway between release point and impact point, (4) at the impact point (when the Norden sighting angle index reads zero), and (5) at a point 50 sec in time from the release point. It is imperative that the airplane fly a straight line course from the beginning of the run until the last picture is taken.

From these photographs it is not only possible to determine where the bombs would have fallen, but it is also possible to determine how the error was divided among such things as course errors, altitude errors, and bombsight error.[72]

This method of bomb scoring was used on a mass production basis at Victorville AAF for many months. The average photo scoring error encountered was stated to be considerably under 100 ft from 10,000 ft altitude.

PHOTOGRAPHY FROM THE GROUND

Introduction. The photo-theodolite method as developed at the Radiation Laboratory[23] fulfills requirements 1, 4, 5, and 7 of Section 13.1.1 with varying degrees of success. The major advantage of this method is the accuracy obtainable, which is considerably better than that of other methods now available, such as radar tracking, or photography from the airplane. Radar tracking is not very satisfactory for handling runs at low altitudes (around 500 ft).

Another advantage of the method is the relative simplicity of the equipment. No special optical systems are needed — a standard camera is used, and the most delicate adjustment required is easily accomplished with the aid of a plumb bob. The ground installation, exclusive of the communication equipment, weighs about 500 lb, but no single part weighs more than 100 lb. A radio transmitter and receiver for communication with the airplane are also essential.

The ground photography method has some definite limitations, the most fundamental of which is the need for clear photographic visibility. In addition, the maximum bombing error that can be measured is limited by the narrow angle of view of the camera. Thus, the error may be so large that the bombing airplane does not come into the field of view of the camera. This limitation may be modified by another choice of camera or lens. A third restriction is the small number of bombing planes that one photo-theodolite can handle concurrently. In a training program, the last restriction is troublesome.

Description of Equipment. In bomb scoring by photography from the ground, a special vertical photo-theodolite is used. The photo-theodolite consists of a standard 16-mm movie camera which photographs the bombing airplane through a set of wire cross hairs held about 54 in. above the camera. A clock capable of being read to 0.01 sec is photographed along with the cross hairs and the airplane. A 1,000-cycle note broadcast from the airplane is turned off at the bomb release point, and a special circuit on the ground, actuated by cessation of the note, starts the clock. By using very fast film and small camera stop openings, both clock and airplane can be kept in focus.

Method of Operation. The photo-theodolite (see Figure 1) is usually set up as near to the center of the target as possible, although large displacements are permissible provided corrections are made in the final data. The intersection of a set of cross hairs is placed vertically over the center of the camera lens by using a plumb bob. While the airplane makes a bombing run, it is under the control of the automatic pilot and thus is held on the same course after the release point is reached and until it passes over the target. (In Figure 1, the release point is at *A*.) When the plane appears in the camera finder, the camera is turned on and a movie is made which shows the airplane, the set of stationary cross hairs, and a clock which has already been started automatically by a signal from the plane at the release point.

Method of Analyzing Photographs. When an analysis of the photographs is made, the frame is selected which shows the airplane (the center of the bomb bay is taken as the reference point for measuring distances) at its closest approach to the intersection of the cross hairs. On this frame, the number of seconds since the release point is read from the clock. The difference between the clock reading and the known time of fall of the bomb, when multiplied by the ground speed of the airplane, gives the distance from the theodolite to the point of impact of an idealized bomb (range error). Such a bomb would have zero trail and would remain directly under the airplane as it fell (see Chapter 6). The effect of trail can be computed, if desired, but zero trail bombs are entirely satisfactory in scoring bombing systems.

The azimuth error is determined by measuring the distance of closest approach of the airplane course to the intersection of cross hairs on the film and converting to the actual distance expressed either in feet or in mils.

Sources of Error. Of the possible errors involved in this method of assessment, one group is associated with the test equipment. Careful tests of the clock and its associated circuits show that the probable error in overall timing is not more than 0.02 sec. For an airplane (or bomb) moving at 180 mph, 0.02 sec corresponds to about 5 ft in range.

Errors in establishing the vertical depend on the care with which the intersection of cross hairs is placed over the center of the camera lens and the certainty with which this relation is maintained. By using a plumb bob, the lateral displacement between the center of the lens and the cross hairs can be held to less than $\frac{1}{16}$ in. This means that the vertical is established with a radial error of not more than ± 0.75 mil. Similarly any lateral displacement caused by the hair mount is smaller than $\frac{1}{32}$ in.

The second group of errors is related to the accuracy with which the plane follows the same course after the release point as before. This error is not clearly known. The most definite statement that can be made about it is that, on the basis of the bombing tests which have been made with this system, it appears that the probable deviation of the plane from its course is slightly, if at all, greater than the probable deviation of the bomb from its predicted course. A more complete description of this photographic method may be found in reference 23.

13.1.3 Bomb Scoring by Use of Ground Radar Systems

INTRODUCTION

A system consisting of the SCR-584 radar and the associated RC-294 automatic plotting table has been successfully used for bombing assessment. The SCR-584 (see Chapter 11) is a radar originally designed to furnish the position coordinates of a flying aircraft to a gun director for the control of antiaircraft fire. When used for bomb scoring, it is connected to the RC-294 plotting device which presents a ground plan view of the flight-path of the aircraft. The plotting scale is 1,000 yards per inch and the maximum plotting radius, 20,000 yd. The information derived from the timed ground track, together with the altitude, wind, and the bomb ballistics, enables the crew of observers on the ground to determine with great accuracy the impact point where bombs would have struck the ground if they had been released from the aircraft at a specified time.

The advantages of the system are:

1. It is independent of weather conditions which would render visual methods, particularly those involving vertical photography or sighting, useless. Training by this method can be carried out in any weather in which aircraft can fly.

2. The accuracy of the instantaneous position data obtained with the system is superior to that provided by aerial vertical photographic methods, most of which have large inherent errors because of the difficulty and uncertainty of camera leveling. Furthermore, the continuous nature of the information permits a more accurate determination of speed than is possible with discontinuous information, such as is obtained from strip photographs. The *circular probable error* [CE] in determination of the impact point is about 100 ft.

3. By virtue of the data recording system used, the impact point computation and the bombing error can be determined much more easily and in a shorter time than by photographic methods. The routine procedure requires only 30 sec after the release time for computing and radioing the information back to the aircraft.

4. The technique makes it possible to solve the bombing problem completely without the use of data from the aircraft other than the release-point time. This is particularly advantageous in training operations, because it provides an overall check upon the data obtained and used by the bombardier in the aircraft during the bombing run. Moreover, by comparing the position and ground track of the airplane, as obtained by the radar system at several points, with corresponding information from the airplane radar operator and bombardier, it is possible to resolve the whole bombing error into its several components. Most photographic scoring methods utilize data obtained by the bombardier, and are therefore not independent of errors he may make or of instrumental errors in the equipment in the aircraft.

Several other methods for using the data derived from the SCR-584 for bombing assessment have been devised. These include (1) timed intermittent photography, or moving picture photography of the slant range, elevation and azimuth dials of a "data-box" attached to the SCR-584 data output selsyn system; (2) calibrated recording voltmeters attached to the data output potentiometer system; (3) manual plotting boards; and (4) other types of automatic plotting boards, for example, the MC-627 plotter (see Chapter 11). The RC-294 has the advantage over all photographic methods, including (1) above, of being much more rapid in operation and requiring no tedious manual plotting of the data. It is more accurate than the recording voltmeter system and it is simpler to calibrate, operate and maintain than the MC-627 plotter.

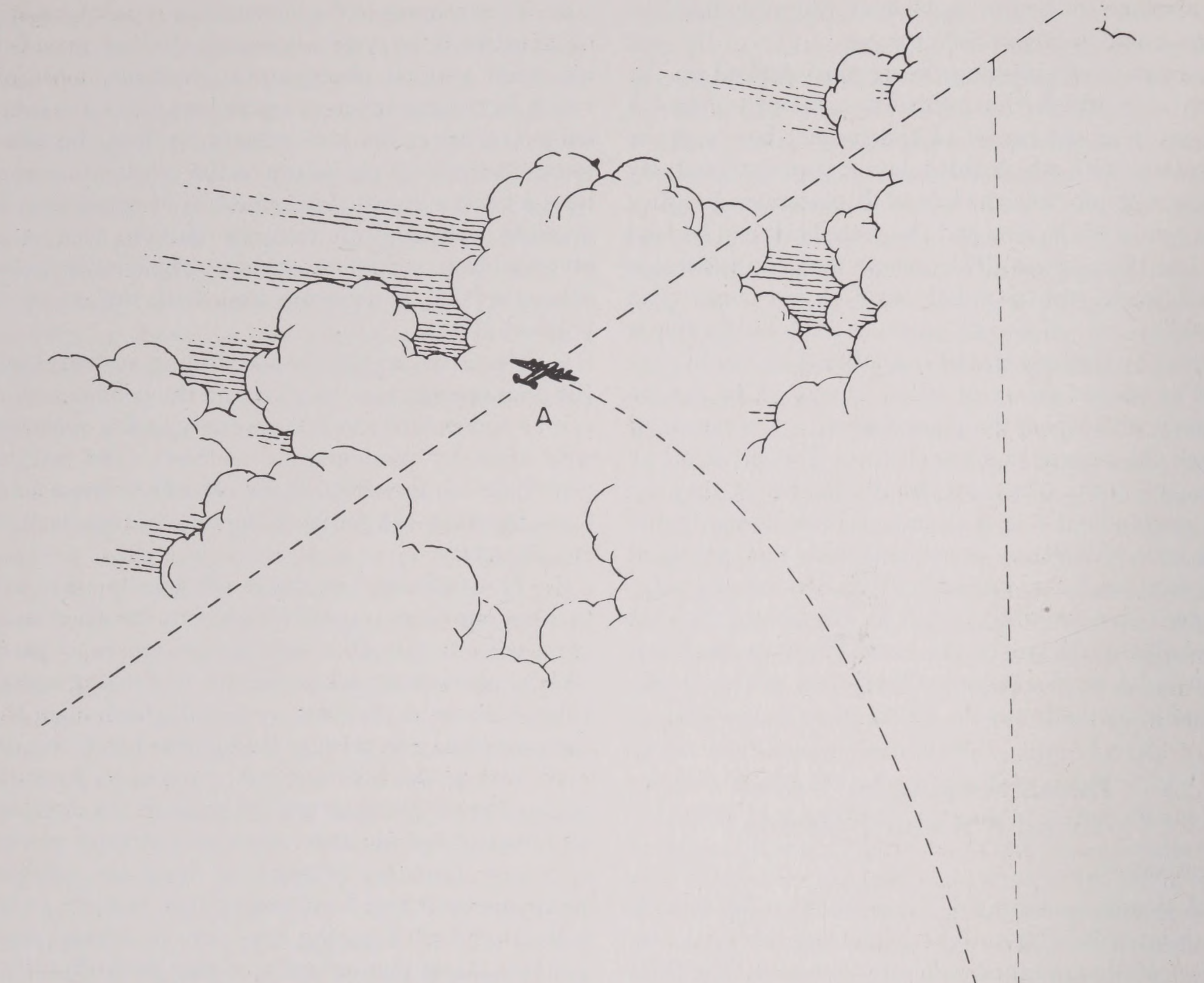


Figure 1. Vertical theodolite in use beside a corner reflector.

EQUIPMENT

A block diagram of the SCR-584 and RC-294 plotting system is shown in Figure 2 and a sketch of a typical field installation in Figure 3. The SCR-584 provides azimuth and range data from 1/1 to 16/1 speed selsyn generators attached, in the case of azimuth, to the azimuth gearing of the antenna mount, and in the case of range, to the SCR-584 Ground Range-Altitude Converter Data Unit which has been modified to provide 1/1 and 16/1 selsyn output (see Figure 2).

The azimuth and ground range data from the SCR-584 feed into two similar, separate servo-channels in the RC-294, one for azimuth and the other for ground range. A close-up view of the selsyn and drive-motor assemblies of the RC-294 plotting-table mechanism is shown in Figure 4, and a simplified schematic diagram of one servo-channel in Figure 5. The channels operate as position servos and determine the azimuth position of a horizontal boom and the radial position of a small "range-cart" that rides on the boom. The boom and range cart establish the position of the pen which writes on the under surface of the tightly stretched plotting paper (see Figure 4). The top of the plotting paper is left free for the use of drafting instruments required for computing the bomb impact point. Instead of making continuous contact with the plotting paper, the plotting pen strikes it at one second intervals so as to provide a record of the time. Every tenth dot is extended to form a dash for ease in counting (see Figure 6). The relay which operates the pen is continually actuated by a clock circuit, but may also be operated by a 1,000-c tone received via the radio from the bombing airplane.

High frequency [HF] and *very high frequency* [VHF] transmitters and receivers are provided for ground-to-air communication, and there is an intercommunication system between the SCR-584 and RC-294 vans.

Altitude information on the aircraft being tracked can be transmitted to the RC-294 from the SCR-584, where it appears on the dial of a selsyn repeater when the SCR-584 Ground Range-Altitude Converter system is switched to the altitude position. It is necessary to interrupt the ground track for about 10 sec to obtain an altitude reading in this manner.

A description of the Radiation Laboratory *radar bombing training* [RBT] plotting system may be found in reference 20. The RC-294, which is based on the RBT system, is fully described[94] with complete installation, operation, and maintenance procedures. A redesigned version of the RC-294, designated as the RC-310, embodies a number of improvements in mechanical design but is otherwise identical.

Unless very high accuracy is desired, no special equipment is required in the airplane for bomb scoring with the RC-294. The so-called voice procedure requires the bombardier to call out the instant of bomb release over the aircraft radio so that the plotting table crew may mark the point upon the ground track. Timing errors up to 1 sec, corresponding to 440 ft at 300 mph, are inherent in this procedure because of the slowness of human response.

A more precise method of marking the release point is afforded by the release-point indicator AN/ARA-17. This device is connected directly to the Norden bombsight so that, when the bombsight indicates the bomb release point, the airplane transmitter is turned on and sends out a 1,000-c tone for a period of 1.5 sec when triggered by the release impulse. As previously mentioned, the 1,000-c tone automatically operates the plotting-pen relay and marks the plotting paper for the duration of the tone. The total overall time delay from release impulse to marking of the paper is less than 0.1 sec, which represents only 44 ft at 300 mph. The release-point indicator [32] illustrated in Figure 7A and B operates on 24 volts d-c and weighs 9 lb.

OPERATION

The SCR-584 and RC-294 system is usually located about 10,000 yards from the major target in the target city, so that bombing runs from any direction may be recorded on the plotting paper. In preparing the system for operation, there are two important problems to be solved, aside from the technical operation. These are (1) obtaining the range of the target or targets from the SCR-584; and (2) orienting the SCR-584 or the plotting-table boom so that the position of the target on the plotting surface corresponds to the actual position of the target with respect to the SCR-584. In the exceptional cases, where the target is visible from the position of the SCR-584 and, in addition, provides an unambiguous radar echo, the positioning and orientation problems are simple. The SCR-584 is merely locked on to the target, and the corresponding position of the plotting pen indicates the proper location of the target on the plotting surface. In cases where the target is visible, but does not provide a suitable radar echo, the telescope on the SCR-584 antenna mount provides a means for obtaining the bearing or azimuth of

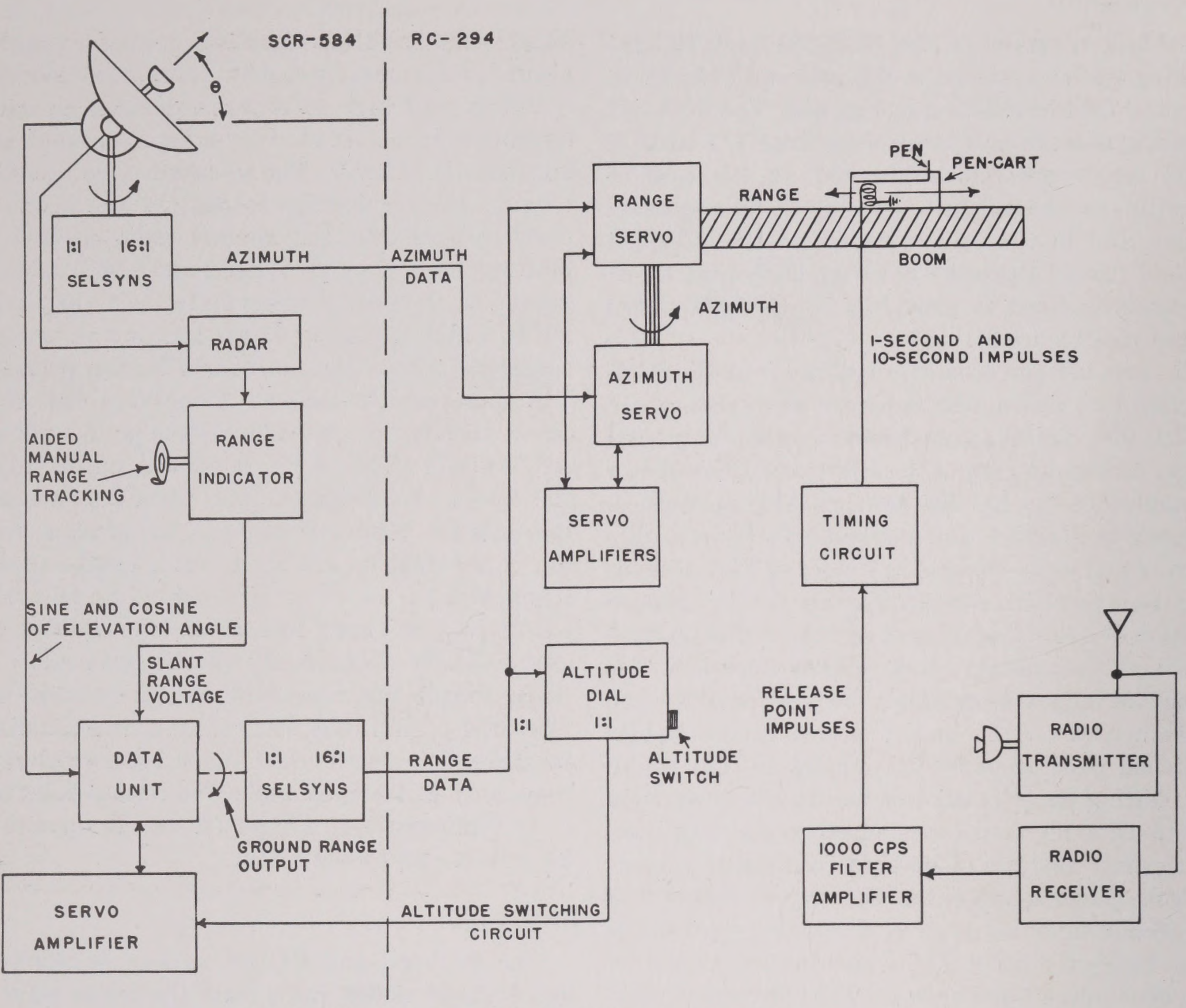

SCR-584
RC-294
θ
1:1 16:1
SELSYNS
AZIMUTH
AZIMUTH DATA
RADAR
RANGE INDICATOR
AIDED MANUAL RANGE TRACKING
SINE AND COSINE OF ELEVATION ANGLE
SLANT RANGE VOLTAGE
DATA UNIT
1:1 16:1
SELSYNS
GROUND RANGE OUTPUT
RANGE DATA
SERVO AMPLIFIER
ALTITUDE SWITCHING CIRCUIT
RANGE SERVO
AZIMUTH
AZIMUTH SERVO
SERVO AMPLIFIERS
ALTITUDE DIAL
1:1
1:1
ALTITUDE SWITCH
RANGE
PEN
PEN-CART
BOOM
1-SECOND AND 10-SECOND IMPULSES
TIMING CIRCUIT
RELEASE POINT IMPULSES
1000 CPS FILTER AMPLIFIER
RADIO TRANSMITTER
RADIO RECEIVER

FIGURE 2. Block diagram of SCR-584 with RC-294 plotting table.

the target; but the ground range of the target must be obtained from scale maps, survey data, or other means, and set in to the range tracking unit manually.

When the target is not visible from the SCR-584, it is necessary to resort to standard artillery procedure for obtaining the range and bearing of the target. A direct method of high accuracy is to carry aloft, over the target, a radar corner reflector suspended from a meteorological balloon whose position is accurately controllable by means of three guy ropes. The SCR-584 is "locked on" to the corner reflector and its position marked directly on the plotting table. This method is accurate to within a few feet providing care is exercised by the crew of the SCR-584 in calibrating the entire radar system.

Once the target positions are known, they may be reset into each new plotting sheet by means of range and azimuth dial readings in the SCR-584 or by a Plexiglas template. As soon as the target has been marked upon the plotting surface, the system is ready for operation.

As discussed in Chapter 6, the velocity and direction of the wind must be obtained in order to get a complete solution of the bombing problem. This is done by having the aircraft fly a wind triangle when it arrives in the range area for bombing practice. In this operation, the aircraft is guided by the plotting-table crew around a triangular course of approximately 2 minutes on each side. A specified constant airspeed is maintained on the straight portion of each leg of the triangle. A typical course is illustrated in Figure 8. After the wind triangle is completed, the aircraft is released and goes out to its first *initial point* [IP] to begin the bombing practice.

Figure 8 illustrates the fact that when the true airspeed vector, $\mathbf{V}_a$, is added at any angle to the wind

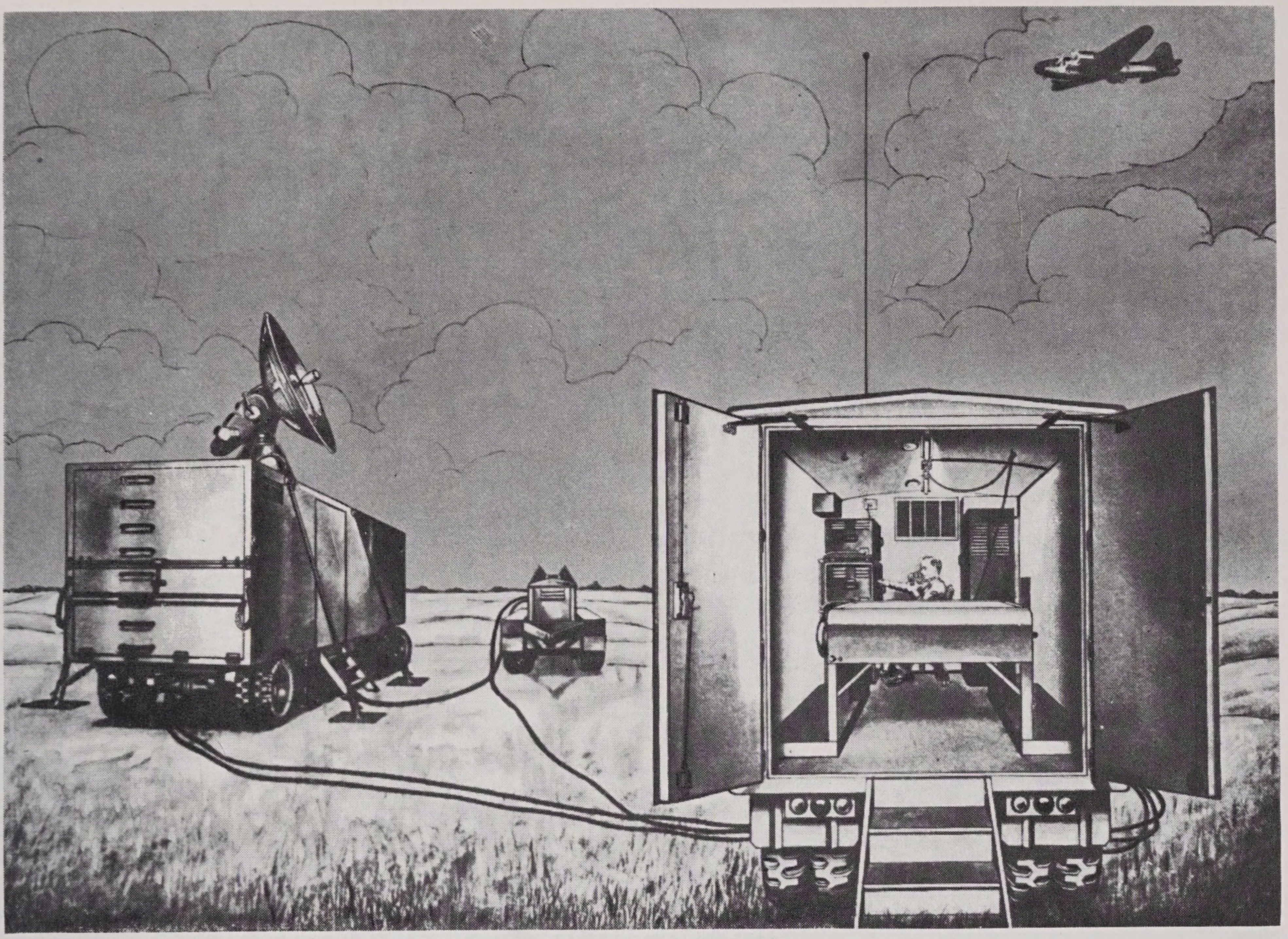


FIGURE 3. Overall view of RC-294 plotting equipment.

vector $\mathbf{W}$ the locus of the vector sum will be a circle of radius $|\mathbf{V}_a|$ centered about the head of the wind vector. The sum will always be the ground-speed vector $\mathbf{V}_g$ and for any given heading will be measured from the tail of the wind vector to the head of the airspeed vector. For example, the airspeed vector $\mathbf{OA}$ is equal to the sum of the wind vector $\mathbf{W}$ and the ground-speed vector $\mathbf{PA}$.

The inverse of this process is used to find $\mathbf{W}$ and $\mathbf{V}_a$ from the three ground-speed vectors obtained on the three legs of the wind triangle, as shown in Figure 8. To obtain the maximum variation in length of the three ground-speed vectors, they should be approximately 120 degrees apart, although any angles can be used. They are drawn to scale from a common point and a circle is circumscribed about their heads. The radius of the circle is the true airspeed, $|\mathbf{V}_a|$, and $\mathbf{OP}$ is the wind vector. The accuracy of the determination depends upon the care exercised in measuring the ground-speed vectors, the ability of the pilot to hold a steady course, the constant airspeed along the sides of the wind triangle, and the precision of the geometrical construction. Wind and true airspeed data, obtained in this way, are usually accurate to better than 5 mph.

The typical procedure followed during the bombing run consists of observing the aircraft on the *plan position indicator* [PPI] of the SCR-584 (out to 70,000 yd, maximum) until it comes within automatic tracking range (32,000 yd), after which the tracking is switched to automatic. Just before the aircraft comes within 20,000 yd (maximum plotting range), the RC-294 crew makes an altitude reading. As the aircraft nears the estimated release point, the automatic release-point circuit is switched on and when the 1,000-c release signal is received, the release point is automatically marked on the plotting surface, as illustrated in Figure 6. Once the release point has been marked, the aircraft immediately turns off the bombing course; and the SCR-584 may start tracking a second aircraft on its bombing run while the first aircraft is preparing to make another run.

If the plotting crew is skilled in traffic control and the initial point is sufficiently distant, several aircraft may be handled and a release may be made as often as once every 5 minutes. Normally, however, only one or two planes are controlled simultaneously and a score is made about every 10 minutes. It must be emphasized here that the problem of traffic control and identification of the aircraft making the bombing runs presents a major difficulty in the operation of the RC-294 system (or of any other ground-based system). Identification, when a number of airplanes are being monitored, is usually accomplished by directing the pilot to make an identifying 90-degree turn, and observing this maneuver on the PPI or plotting table. For a large-scale training program, either an auxiliary traffic-control radar, a direction finder or the use of beacons, would aid materially in solving the identification and in increasing the traffic handling capacity of the system.

The geometry of the bombing problem is shown in Figure 9 (see also Chapter 6). The general discussion or solution of the bombing problem from ground based radar systems is presented in Chapter 11. A typical ground track with the bomb release point marked on it is shown in Figure 6. The ground speed $|\mathbf{V}_g|$ may be found by measuring the distance covered in a given number of seconds and using an appropriate conversion factor. In Figure 9, AC is equal to that length of ground track which corresponds to the number of second marks equal to the time of fall of the bomb. The construction establishing the impact point, E, may be completed from wind and bomb ballistics data. The techniques of calibration, orientation, and plotting of the RC-294 system are described in reference 31.

An extensive program of practice bombing error analysis was set up by the Army Air Forces during the last 6 months of World War II. The analysis was made possible by information derived from various scoring methods such as the RC-294 and Camera Bombing (Section 13.1.2, "Aircraft Camera Method").

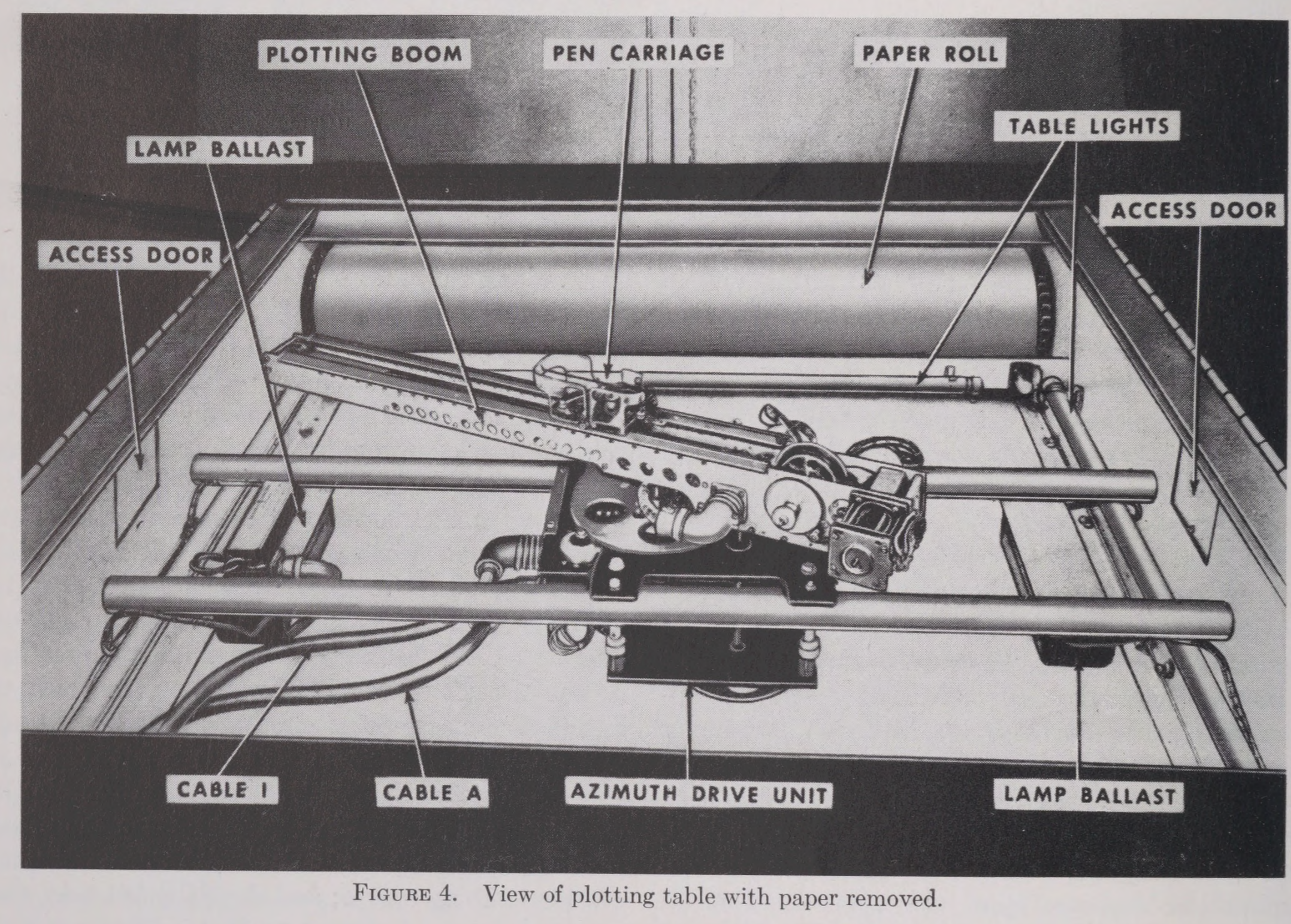


FIGURE 4. View of plotting table with paper removed.

ACCURACY

The major sources of error inherent in the SCR-584 and RC-294 plotting system are a function of the distance of the SCR-584 from the target, the altitude and airspeed of the aircraft, and the care exercised by the plotting crew in operating the system and computing the impact point. If the speed, altitude, or heading of the aircraft is varied appreciably during the portion of the bombing run over which the measurements are taken, an unknown amount of error will be introduced into the result. However, such a bombing run would be worthless from the standpoint of the operation of the bombsight in the aircraft and would normally be disregarded.

The following tables illustrate the major sources of error and the probable errors (PE) to be expected from them in the specific case of an aircraft flying at 200 mph true airspeed, 23,000 ft altitude, at right angles to a 50-mph crosswind. The time of fall is taken as 40 sec, and the target is assumed to be about 10,000 yd from the SCR-584.

TABLE 1. Typical probable errors (PE) in determination of bomb release point using RC–294 system.

PE	Yards
In orientation of the SCR–584 ($\frac{1}{2}$ mil)	5
In aligning telescope and radar axis ($\frac{1}{2}$ mil)	5
In slant range from SCR–584 (tracking error)	15
In plotting due to azimuth tracking error (1.6 mils)	16
In plotting due to elevation tracking angle error (1.6 mils)	11
In triangle solver (SCR–584 data unit)	8
In release point mechanism (after subtracting fixed delay)	5
In reading dot position	3
$(\Sigma \overline{\mathrm{PE}}^2)^{\frac{1}{2}}$ = Total PE in position of release point with respect to target	28

TABLE 2. Typical probable errors (PE) in computing the impact point using the RC–294 system.

PE	Yards
In extrapolation of ground track ($\frac{1}{4}$°)	16
Introduced by timing clock (0.2% of $V_g \cdot t_f$)	8
In computing cross trail (wind and airspeed determination)	5
In time of fall (± 30 yd error in altitude)	10
Total PE in computation of impact point	21

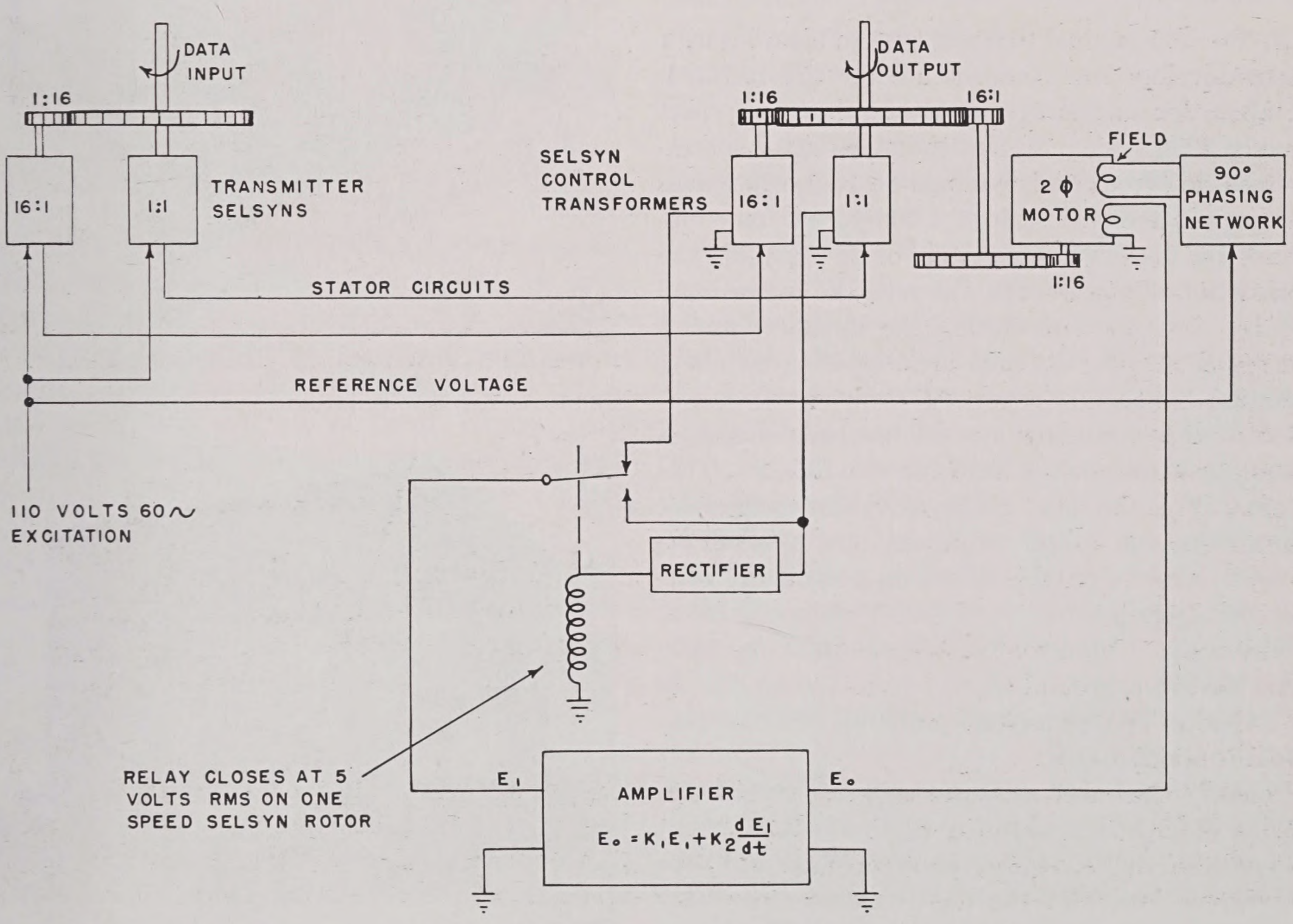

DATA INPUT
1:16
16:1
1:1
TRANSMITTER SELSYNS
SELSYN CONTROL TRANSFORMERS
DATA OUTPUT
1:16
16:1
16:1
1:1
FIELD
2 φ MOTOR
90° PHASING NETWORK
1:16
STATOR CIRCUITS
REFERENCE VOLTAGE
110 VOLTS 60~ EXCITATION
RECTIFIER
RELAY CLOSES AT 5 VOLTS RMS ON ONE SPEED SELSYN ROTOR
E1
Eo
AMPLIFIER
Eo = K1E1+K2 dE1/dt

FIGURE 5. Servo block diagram.

The resultant probable error in impact point determination with respect to the target is 35 yd. These accuracy figures have been checked, roughly, by photographic methods at the Radiation Laboratory and by bombing trials at the AAF Proving Ground in Florida.

It is clear from Tables 1 and 2 that the major source of error is the SCR-584 tracking system. A new version of the SCR-584 known as SCR-584X incorporates a tracking system with probable error only one-third that of the SCR-584. The SCR-584X would be the logical substitute for the SCR-584, in applications where greater accuracy than that quoted above is desired.

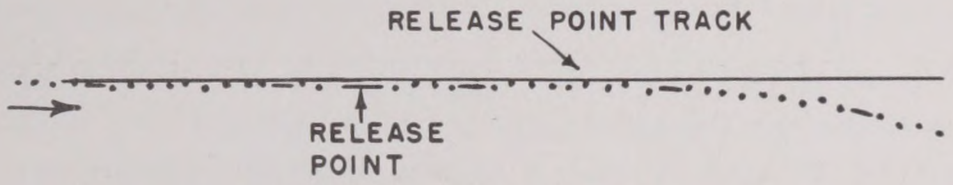


FIGURE 6. Ground track.

OTHER RADAR BOMB SCORING METHODS EMPLOYING THE SCR-584

The RC-305 manual plotting system is an interim system developed as a substitute for the RC-294. The operation of the system is identical with that of the RC-294 system, except that the data is manually recorded from dial readings at 10-sec intervals and then plotted on a scale of 1,000 yd per inch. Because of the discontinuous nature of the data and the introduction of the human element, the operational probable error in determining the impact point is about 125 yd. The RC-305 is fully described in a Radiation Laboratory report.[36]

A recording voltmeter system has been proposed as another interim substitute for the RC-294. This system utilizes the slant range, elevation cosine, and azimuth sine and cosine potentiometers in the SCR-584 and presents on the recording voltmeter, voltages corresponding to the X and Y components of ground range. The recorded data are then manually transcribed to a ground track plot as in the case of the RC-305. The estimated probable error of this system is about 100 yd.

Probably the most accurate scoring system embodying the SCR-584 is one in which the data output dials of the SCR-584 are photographed at 1-sec intervals or less, and the data are later carefully plotted manually. Because of the time element involved, this method is not as convenient to use for training as the RC-294 system. It is probably the best method for obtaining experimentally such items as the complete trajectories of aircraft under test, and bomb ballistic data.

13.1.4 Bombing Assessment from PPI Photographs

The assessment of bombing accuracy from PPI scope photographs presents a number of interesting features despite the limitations of the method. In H2X bombing, it is necessary to take a series of scope photos during the bomb run, preferably spaced equally in time and at 10-second or shorter intervals.

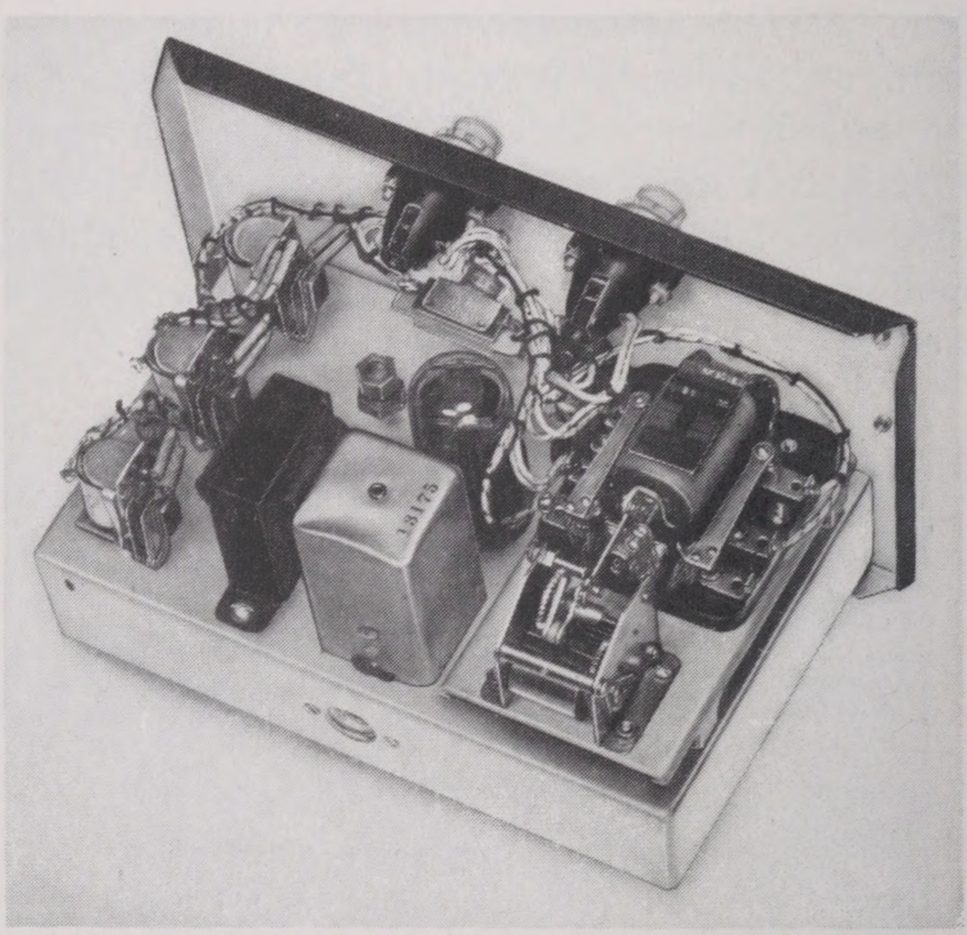


FIGURE 7A. Top view of release-point indicator.

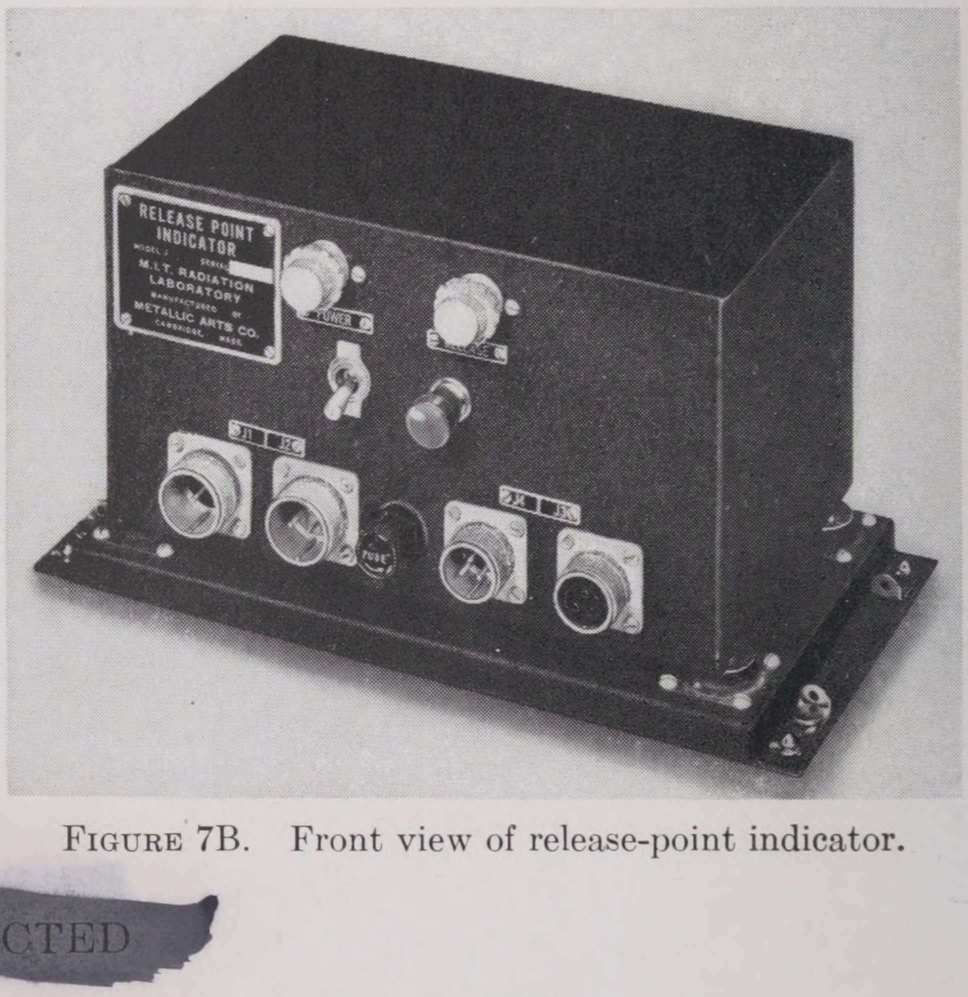


FIGURE 7B. Front view of release-point indicator.

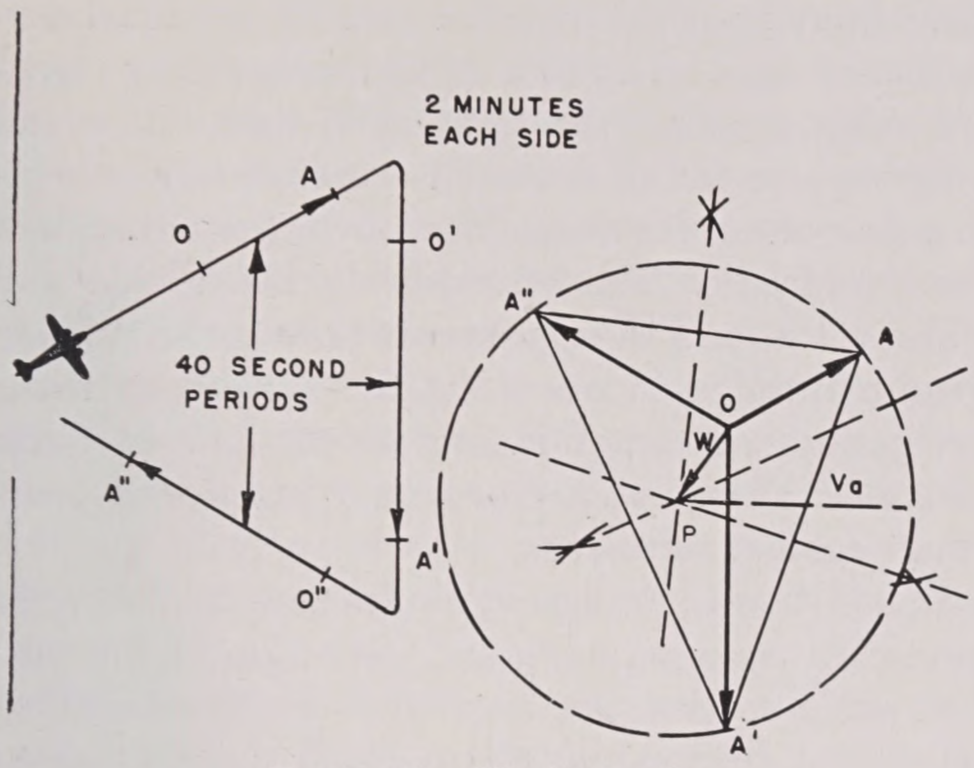


Figure 8. Wind triangle.

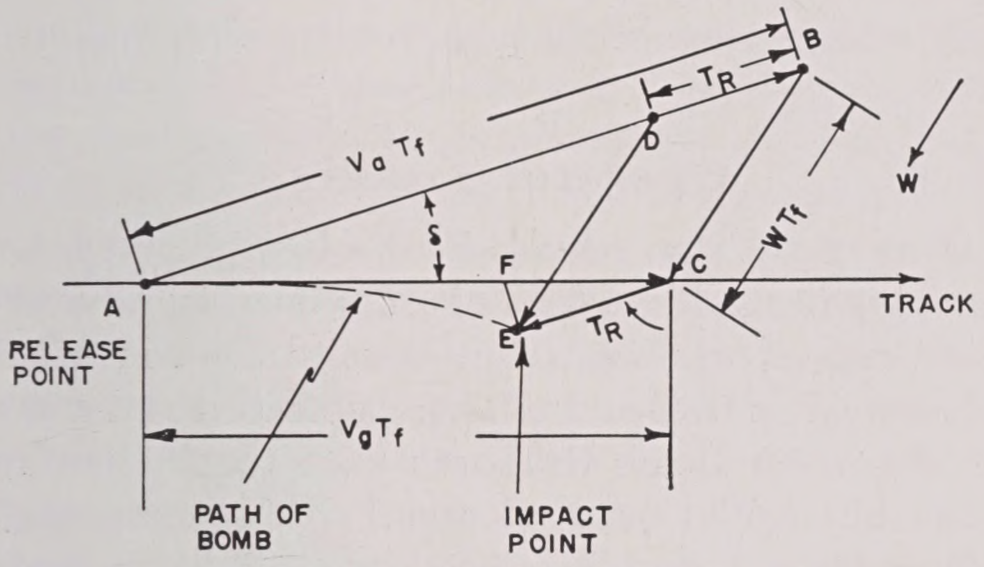


Figure 9. Bombing diagram.

The instant of bomb release should be indicated by a signal light in the corner of the picture or some equivalent method.

Plotting of the location of the successive photos on a suitable map will enable one to determine course, ground speed, and location of bomb release, from which impact can be determined. The series of pictures should include several after the time of bomb release.

Estimates of the accuracy of this method of determining impact point run from one-quarter mile to a mile or more. One-quarter mile is probably optimistic, even under the best conditions. A full rotation of the scanner requires 3 sec and the aircraft travels approximately one-fifth of a mile in this time. With everything else perfect, the uncertainty of location of a single picture (3-sec time exposure) must then be one-fifth of a mile. On the other hand, the upper limit of accuracy depends upon accurate plotting of each photograph. In general, for photographs taken as the bomb release point is approached, plotting becomes more difficult, since the operator usually has expanded the scope to some unknown radius, removed the range marks, and readjusted the receiver gain. This difficulty can be partially overcome by the practice of restoring the scope to a predetermined adjustment, including range marks, just prior to bomb release.

Even granting that the accuracy of the method is probably no better than one-half mile, there are several reasons for using it. The uncertainty is free from bias with perhaps one exception — if the H2X set is performing very badly, the photographs will be unsatisfactory and the bomb run will also be poor. On the other hand, assessment by strike photos or photo reconnaissance is likely to be very biased.

If photo reconnaissance is used, bomb craters well away from the target, especially in open areas, are easily seen. On the other hand, craters near the target may be difficult or impossible to locate. This is particularly true when the target is an industrial plant made up of similar buildings.

If photo reconnaissance is discounted, as was done by the Operational Analysis Section of 8th Air Force, and strike photos are used, we are faced with another bias. Planes flying wide of the target are likely to get recognizable pictures of the ground, while those flying directly over the target will be more likely to find the ground completely obscured by haze and smoke from the target itself. Therefore, the most satisfactory strike photos will show large bombing errors.

Entirely aside from the question of accuracy, it was found at 8th Air Force that assessments based on scope photos and made by a special section of the Photo Wing could be in the hands of the operating squadrons within two days of the mission; the results from the more careful analysis of strike photos were not completed until 3 or more months later. By this time, most of the value for improvement in technique has been lost, as frequently the bomber crews concerned had returned to the United States.

In this connection, the use of movie cameras should be mentioned. In addition to the above possibilities for assessment, the continuity of the projected movie print presents information on the entire mission that cannot be obtained in any other way. It is possible to assess the execution of the rendezvous, cross-country navigation, turning at initial point, and execution of the bomb run. Such difficulties as killing drift and departures from briefed courses in navigation can be seen at once. With proper facilities, a print can be projected at a squadron critique within 2 hours of landing time. These extra advantages are very valuable in improving the overall of teamwork between radar operator, navigator, bombardier, and pilot.

Evaluation of the accuracy of a Micro-H mission from scope photographs is not as easy as for an H2X mission. This is true because only the beacon signals are visible on the PPI photographs. The general execution of navigation can be assessed by an examination of a series of photographs, or better yet, a viewing of a movie film made up of successive time exposures of the scope. Unless an additional movie of the computer drum settings is made, no very good evaluation of impact point can be made. Errors in range computation, errors in calibration, errors caused by malfunctioning of the range unit, and errors resulting from careless setting of the computer drum, will not show up on photographs of the scope. Motion pictures of Micro-H missions, however, would permit a general evaluation of the smoothness of execution of the mission which would be of considerable value in pointing out and correcting mistakes of inexperienced crews.

13.2 TRAINING

13.2.1 Introduction

The large-scale introduction of any new equipment into the Armed Forces always imposes the formidable task of training the personnel to utilize it properly. The purpose of this section is to outline some of the problems encountered in radar training during World War II and to describe their solutions together with some recommendations for future peacetime training procedure. Training for microwave airborne radar bombing will be used as an example of the complex and diverse problems that arise in all phases of radar training including aircraft to surface vessel and fire control.

A radar bombing mission can be divided into two parts — planning and execution. Planning implies that the headquarters staff has been trained sufficiently to recognize the capability and limitations of the radar equipment. Adequate radar reconnaissance and analysis personnel should also be located at headquarters to permit selection of targets suitable for radar attack. Moreover, intelligence officers who brief the combat crews should be well-trained in all aspects of radar navigation and target identification.

Execution of the mission necessitates, first of all, that the equipment be operational, that is, it must have been properly installed and its technical performance must be up to a certain satisfactory standard. This involves the training of installation and maintenance technicians and establishment of routine procedures for assessment of the performance of the equipment. The operators (enlisted men and officers) who use the equipment during the mission require training in operating the system, in radar navigation, in target identification, and in radar bombing. The combat crews need practice in operating together as teams.

In addition to the headquarters personnel directly connected with planning and execution of the mission, other sections are required, such as a bombing assessment and analysis group which must be trained to evaluate bombing performance. A theater training group must also be available to devise and supply any additional operator and crew training required.

13.2.2 Operator Training

One of the first schools in the United States for training in the techniques of radar bombing of overland targets was located at Grenier Field in Manchester, New Hampshire. There, operators and crews of the 812th Bomb Squadron were taught how to use the (initial preproduction) H2X equipment. These crews were destined to lead the 8th Air Force as pathfinders during the winter of 1943–1944. Since no Army personnel had ever been trained in the use of this equipment, there were no available Army instructors; consequently the designers at the Radiation Laboratory acted as instructors. These men were well acquainted with the technical features of the equipment, but at the time, were unaware of some of its serious limitations. Neither were they completely familiar with the bombing problem. However, the navigators and bombardiers, who started learning how to operate the radar equipment, supplied the needed knowledge and readily worked out a radar bombing technique. A partially successful effort was made to assess the resulting bombing performance by photographing the impact point through a Norden bombsight synchronized with the radar.

After a short period of training, the crews flew to the European Theater to start operations. In the interests of speedily supplementing the original twelve H2X crews in the theater, the training pattern established by the original group at Grenier Field was abridged to such an extent that the new crews who went into combat theaters from the

United States had too little training. As a result, large theater training programs had to be set up before the most effective use could be made of the equipment. Because of the difficulties of training under theater conditions, it was never possible to completely realize the instrumental capability of this radar equipment in the European Theater.

The experiences of the 8th Air Force, noted above, are typical of the early training programs in which the air forces were attempting to build a successful training program that would produce the best results in the theater within the time limit imposed by expediency.

By the end of the war, it appeared that an adequate operator training program should involve the following four major phases.

1. *Individual ground school training* where the student learns the rudiments of navigation and bombing procedure, interphone technique, scope interpretation, and operation of the controls of the radar set. He then utilizes his newly acquired knowledge on a supersonic trainer to obtain simulated bombing and navigation experience. (The supersonic trainer embodies a miniature scale model of the terrain immersed in a water tank which is scanned at supersonic frequencies by means of a crystal. The images produced on the PPI scope are remarkably similar to those which would be seen on the radar when flown over the corresponding territory.[27]) An important feature of the training program is competitive scoring of the student's proficiency. It is also important to have instructors who are well qualified to teach their subject. In the interests of uniformity, the instructors should be supplied with a specific lesson plan including briefing material in a form of an instructor's manual, for example, the APQ-7-T1 trainer published by the Training Aids Division.

2. *Advanced flight training* where the student is flown over many different complex targets in order to gain proficiency in scope interpretation. The initial phase of this training consists of teaching the student the fundamentals of drift-killing, wind measurement, and operation of the set including computer manipulation. This is accomplished by running a few missions on pin-point targets where scope interpretation is no problem. After the initial phase, the student is flown over complex targets to learn the technique of scope interpretation.

The two vital elements of this program are proper briefing of the operator with scope photographs before the mission and scoring of his bombing performance. Since target identification has been consistently the largest source of error in radar bombing, an automatic scope camera is a very important accessory to this phase of the training program. It is axiomatic that the student will generally make little effort to correct his ways unless he is firmly convinced of his error. With the photographic record of the student's individual performance before him, the instructor can easily convince the student of his errors, for example, in target identification or in failing to kill drift properly. The effectiveness of scope cameras thus utilized was clearly demonstrated by the combat experience of the 315th Wing of the 20th AAF in monitoring the bombing procedure of their AN/APQ-7 radar operators and effecting corrections to their techniques.

3. *Continuation training* to as great an extent as possible while the student is in transit or waiting for operational duties at staging areas. In many instances, the long time interval between the end of formal training and the beginning of combat experience results in the student forgetting practically all he has learned during the training courses.

4. *Theater training* in which the student is subjected to refresher courses in the fundamentals, intensive synthetic training for the purpose of maintaining proficiency in scope interpretation and for studying new target areas, and such flight training as is required for modifying previous training ideas or introducing new ones to suit the peculiarities of the theater. In general, theater training has been found to be difficult. It is often hasty; bomb scoring and other evaluation methods are difficult to operate and maintain in the theater; and the normal tendency is for the operators to go into combat as soon as they show any signs of having mastered the technique, even though they may not have become reasonably proficient. Without question most of the training should be accomplished in the United States and theater training restricted to the bare minimum necessary for refresher training and for introducing techniques peculiar to the theater.

13.2.3 Maintenance Training

The operational success of a radar bombing device depends fundamentally upon two factors: (1) the equipment must perform reliably and accurately at all times, and (2) the combat operator must have complete confidence in its reliability, accuracy, and capability. Since good maintenance underlies the proper technical operation of the equipment, it would appear that the success of the entire program depends critically upon the quality of the maintenance. It must be emphasized that the training of ground maintenance mechanics is as essential to obtaining good operational results with the equipment as is adequate operator training. This is particularly true of the more fully automatic computers such as GPI (Chapter 9).

The purpose of the maintenance training program is to familiarize the maintenance mechanics completely with (1) the system on which the measurements are to be made, (2) the reasons for making the measurements, (3) the test equipment, and (4) the operation of the test equipment. Besides a thorough instruction in the basic principles of operation of the radar system and associated equipment, the maintenance personnel require sufficient operational experience to enable them to perform the measurements with ease and facility and to make the indicated adjustments or repairs.

In addition to training on the technical aspects of operating, servicing, and maintaining the equipment and evaluating its performance, there is another phase of training on matters of supply, maintenance records, and standard operating procedures for maintenance.

These two types of training are required for personnel in first, second, third, and fourth echelons of maintenance; in the supply corps which must become familiar with the new equipment in order to estimate, order, and stock supplies; and in the headquarters organization which will be responsible for establishing the level of equipment maintenance.

The division of maintenance personnel into the echelon category suggests a corresponding division of the training program, since personnel in the first category do not require the same skills, and consequently the same type of training, as those in other categories.

Although most of the training activities can be handled entirely in the United States, the modifications to equipment, that inevitably occur during wartime, always necessitate some theater training.

In connection with maintenance, it cannot be too strongly recommended that the designers be allowed to become familiar with the maintenance problems that arise in the field and how such problems are handled, so that the equipment can be designed for easy maintenance. It is also desirable in this regard, that the Technical Training Commands in the United States become familiar with the equipment during the design stages so as to be in a good position to foresee the training problems, the requirements for training aids, and the requirements for maintenance mechanics to operate the equipment during the initial phases of the training program.

A sketch of the organizational requirements for handling a typical maintenance training program is shown in Figure 10. The organization is headed by a representative group from the Technical Training Command. The function of this group is to set up the program at one of the training centers, and consequently it is essential that its members be thoroughly trained through contact with the technical designers and Army tacticians during the design and procurement period. The function of the group of officers from the Air Technical Service Command is to become familiar with the equipment at an early date and to investigate and remedy the various deficiencies which inevitably show up in any new program. Other functions of the organization are to supply experts to supervise the initial training, to instruct local supervisors in maintenance of the equipment being used for the training, to carry on continuation instruction of the maintenance men during the period while the operator training groups are being trained in one of the Continental Air Forces, and to provide continuation training during initial phases of the combat operations until such times as the combat groups can carry on their radar maintenance without further assistance.

The sequence of instruction is of vital importance. If the men are trained before the equipment is ready, they will forget what they learned while they wait, and if they are trained too hurriedly the quality of maintenance will suffer.

It can easily be appreciated that serious consequences will result if the number of men needed in the top blocks (Figure 10) were underestimated or if a miscalculation of the time required to train them were made. To avoid such an occurrence, it is vitally important that training of personnel in the top blocks begin well in advance of the installation program.

Besides instruction in the principles of operation of the equipment, the maintenance team should have actual experience in and responsibility for performing maintenance. For example, it is completely feasible that the men whose job will be to perform first and second echelon maintenance during combat operations can be given the identical job during group training operations in the United States. Although this point may seem too obvious to be mentioned, it

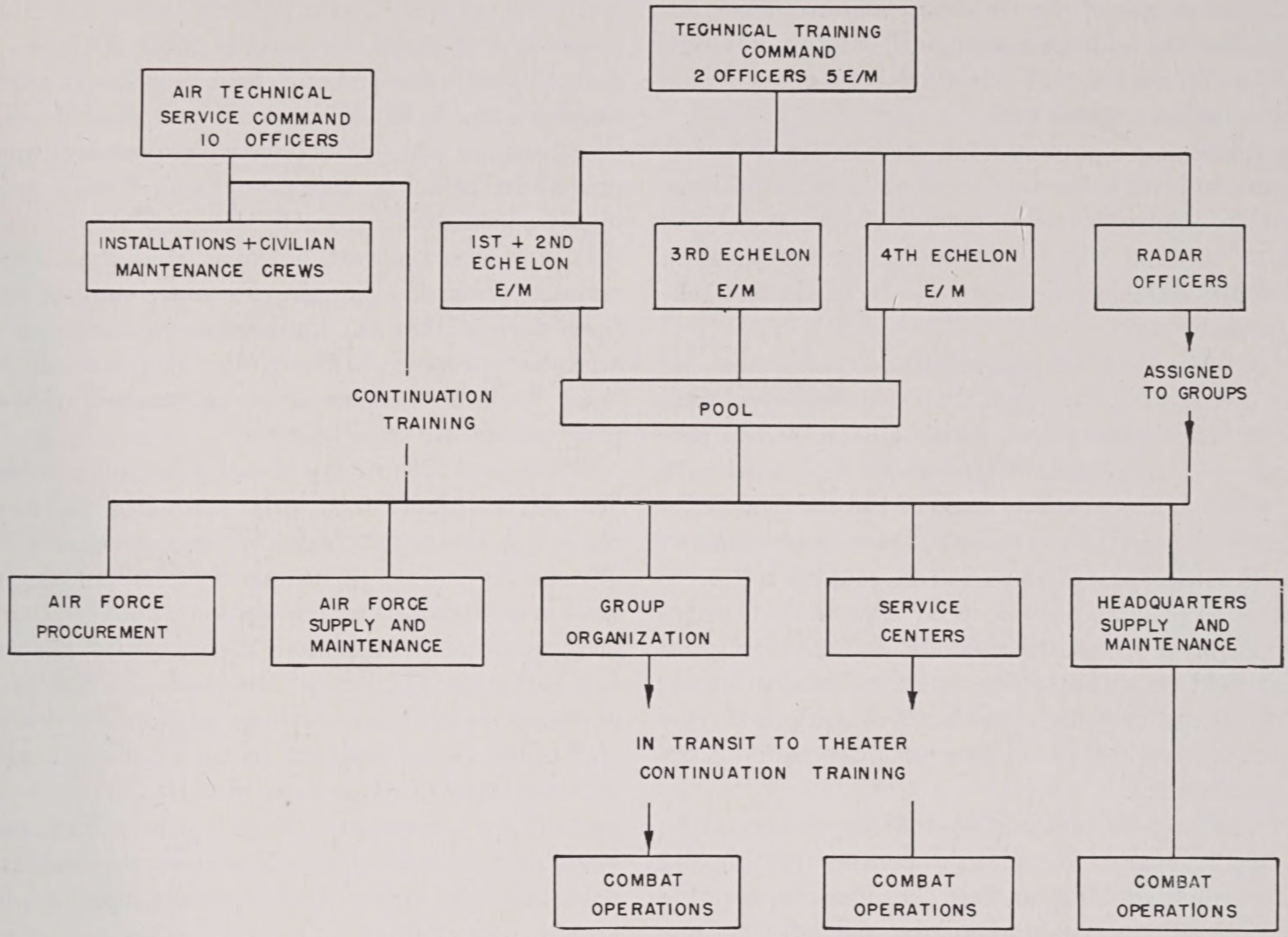

TECHNICAL TRAINING COMMAND 2 OFFICERS 5 E/M
AIR TECHNICAL SERVICE COMMAND 10 OFFICERS
INSTALLATIONS + CIVILIAN MAINTENANCE CREWS
IST + 2ND ECHELON E/M
3RD ECHELON E/M
4TH ECHELON E/M
RADAR OFFICERS
ASSIGNED TO GROUPS
CONTINUATION TRAINING
POOL
AIR FORCE PROCUREMENT
AIR FORCE SUPPLY AND MAINTENANCE
GROUP ORGANIZATION
SERVICE CENTERS
HEADQUARTERS SUPPLY AND MAINTENANCE
IN TRANSIT TO THEATER CONTINUATION TRAINING
COMBAT OPERATIONS
COMBAT OPERATIONS
COMBAT OPERATIONS

FIGURE 10. Maintenance training.

is a fact that this simple method of giving the maintenance men experience prior to combat was not generally employed during the war.

As in the case of radar operator training, in-transit training for maintenance men is highly desirable, particularly if they are required to spend extended periods in staging or rest camp areas.

Moreover, it must be emphasized that the assumption should never be made that men are qualified to perform maintenance simply because they have satisfactorily completed the courses at a service training school. Additional requirements are that they must have obtained a backlog of practical experience by actually performing maintenance work and that the time interval between the end of their training and the beginning of maintenance work in the theater be small.

An essential part of the maintenance training program is the training equipment. Since it often takes as long for radar training equipment to be developed, manufactured, and put into operation as it takes for the development and manufacture of the basic radar, it is obvious that the development and production of radar training aids must parallel that of the radar itself. This is another reason why the training commands should take an interest in the radar from its inception. In addition to training aids, instructor's manuals, instruction and training manuals, instruction course plans and literature, and trainers of various sorts, the training courses also require that the basic radars, spare parts, power supplies, and test equipment be available at the start of the training courses. Because of the nature of maintenance training, it requires a larger ratio of both spare parts and test equipment than is necessary for combat operation, for a student should be expected to make some mistakes which will damage the gear used for training. Such mistakes are a natural part of his learning process and give a reasonable indication that he is doing something on his own initiative.

With regard to the basic radar components, the first units produced should be allocated for training. It is so important that training start as soon as possible that it is usually worth while to have a limited number of systems built on a model-shop basis, prior to mass production, for employment in the initial stages of the training program. This procedure has the added advantage that flaws in design may be discovered and remedied before large-scale production gets under way.

In allocating equipment for the theater, it is important to send more sets than will actually be required in combat installation so that equipments for theater training will be available. In emergencies, this additional equipment can also be used as a backlog of spare parts.

A peacetime training program can, of course, be more orderly and thorough than one developed during the stress of wartime. Although the overall philosophy of maintenance training can be carried over into peacetime operation, some of the training problems are changed. For example, it becomes easier to treat the principles of operation thoroughly but more difficult to provide the necessary experience in actually performing maintenance on a large scale and under field conditions. This is an extremely serious handicap and very high standards of equipment performance must be established in order to keep the mechanics alert.

In contrast to wartime operations, it should be possible to separate completely operator training and maintenance training so that the operator training program will not be hindered by partially trained maintenance men.

13.2.4 Training of Staff Officers

Given well-trained operators and mechanics, the success of the radar equipment depends on how intelligently it is employed by the staff officers who do mission planning, prepare radar intelligence, and provide briefing of the combat crews. This phase of the training program was almost completely neglected during World War II with the result that quality of radar intelligence and briefing varied from group to group depending upon the amount and quality of the theater training obtained on the spot.

Some exceptions to the dearth of trained radar staff officers did exist. Certain groups were able to develop excellent briefing procedures that both interested and stimulated the combat crews. For example, in the 8th Air Force, a radar intelligence group did an excellent job of getting out briefing material such as radar maps and scope photographs of important target areas. A genuine effort was made in this case to obtain good scope photographs and to catalog these in such a way that all group officers could be quickly and easily provided with the information. A similar program was under way in the 20th AAF several months before the end of World War II. As another example, the 315th Wing developed, by the end of the Japanese war, a unique and interesting briefing procedure utilizing fluorescent maps that proved highly successful.

It is now recognized, however, that these theater training programs brought out under combat conditions were neither so complete nor so basic as a well organized program in the United States could have been. Some of the tentative requirements of such a program are outlined below.

Because of the novelty of radar bombing in World War II, a specialist on radar bombing was not included in the regular table of organization of staff officers. As a result, planning of radar bombing missions was often accomplished by a visual bombardier or some other person not fully aware of the capabilities and limitations of the radar. In contrast to planning for a visual bombing mission, in which the staff officers were supplied, by the intelligence group, with all types of maps marked with the latest information on the target and its surroundings, in the beginning radar bombing missions were often planned with only the aid of optical reconnaissance photographs and ordinary maps. As a result the radar bombing missions frequently ended in failure. From this bitter experience, it was learned that not only are detailed photo-reconnaissance and target information from ground intelligence needed, but, also, complete radar reconnaissance information is required so that the appearance of the radar images of the target and its approaches can be studied in detail and memorized by operators and bombardiers prior to the mission. This requirement makes it imperative that radar intelligence officers obtain scope photographs well ahead of the mission so that the best radar approaches and distinctive landmarks for navigation and bombing can be determined.

13.2.5 The Victorville Experiment

Not until mid-1944 was it realized to what extent the lack of operator training was affecting bombing performance in the theater. In an effort to investigate some of the basic features of training, the AAF established the "Extended Training Experiment for H2X" for radar operators at Victorville Army Air Field.[75]

In these experiments a group of twenty graduates of the standard AN/APQ-13 radar observer bombardment course were given considerable additional training to see what improvement could be achieved in their bombing performance. The synchronous bombing technique, in which the radar is synchronized with the Norden bombsight, was employed (see Section 8.3.1). The radar operators were teamed with returned combat bombardiers for the duration of the experiment. All runs on any single routine mission were flown on a single target selected from a total of eleven complex targets. Although the "target familiarity" resulting from making all runs on a single target was undesirable, this procedure was followed to enable the making of more runs per hour than would have been possible on different targets, and to enable the selecting of the target for good photographic weather in order to permit scoring. All runs were scored photographically as described in a Victorville Army Air Field publication[72] (see Section 13.1.2). Each scored run was studied by the student and his errors were analyzed into seven components: (1) drift error, (2) final point deflection error, (3) range error caused by altitude error, (4) radar range error, (5) final point bombsight range error, (6) ground-speed range error, and (7) range error due to time of fall error. Some of the results are given in Table 3.

TABLE 3. Improvement in radar bombing as a function of hours of practice bombing. (Values corrected to altitude of 12,000 ft).

Training period (hours)	Circular probable error (CE), all runs (feet)	Circular probable error, first run on each mission (feet)	Special missions, circular probable error (feet)
0–25	3,137	4,283	
25–50	2,028	2,701	2,590
50–75	1,885	2,426	
75–100	1,627	1,829	1,743
100–125	1,686	2,010	
125–150	1,543	1,767	2,825

At the end of 50 hours, 100 hours, and 150 hours each student flew a special mission over unfamiliar territory and made one bomb run on each of four new targets in order to permit a study of the effect of target familiarity. On all of these runs the operators were briefed with PPI photographs in the usual manner. The results of these special missions are shown in Column 4 of Table 3 and indicate that, except for the 150 hours trial, the circular probable error introduced by bombing totally unfamiliar targets is no greater then the circular probable error of the first bombing run on previously bombed or familiar targets. (The large error in the 150 hours trial may have been due to the operator's boredom and anxiety to finish the experiment and go home. This indication that training could be overdone resulted in the recommendation that the extended training program be limited to 100 hours of main scope time.)

The analysis of scored runs confirmed the belief that inaccurate scope interpretation is the most serious obstacle to accurate radar bombing. The following is a quotation from the Victorville Report.[72] "It is consistently found that the two largest sources of error are the final point deflection error and radar range error. Both of these indicate an inaccuracy in locating the precise aiming point. The importance of these two sources of error can be realized by finding the average circular error if all other types of error were zero. In the first 25 hours, for example, the theoretical circular error produced by the final point deflection error and radar range error alone is 3,005 ft. The average circular error obtained in the first period was 3,137 ft. Scope interpretation alone could account for all the obtained CE. Similar results are obtained for other periods. This does not mean that the other sources of error are negligible. Because certain errors compensate for each other, the total of all the individual errors (neglecting algebraic signs) may be much greater than the total error. Nevertheless, the results indicate that there is sufficient error in scope interpretation alone to produce a CE practically equal to the empirically obtained CE!"

As a consequence of the "extended training experiments" the next large Air Forces Training Program, on radar bombing, namely, operator training on AN/APQ-7 (Eagle) equipment in B-29's, was extended to some extent. This program included: (1) Four weeks (20 main scope hours) of initial operator training at Boca Raton Army Air Base in a course similar to the basic AN/APQ-13 radar operator's course, including supersonic trainer work, practice navigation, dry runs on complex targets, and practice bomb drops on point targets in the water with splash photography assessment. This last procedure provided an evaluation of the student's ability to bomb a point target. (This is a far simpler problem than that of bombing overland targets because scope interpretation is reduced to observation of a single spot on the screen.) The scoring procedure also permitted an appraisal of the student's ability in the fundamental process of killing drift and measuring ground speed. (2) The student radar observer bombardiers then passed from Training Command into the Second Air Force for combat crew training which consisted of two and one-half weeks (26 hours of main scope time) for the 315th Wing and 5 weeks (61 hours main scope time) for the 316th Wing. The Training Command facilities at Victorville Army Air Field were utilized by the Second Air Force for this program. It is significant that, in this course, a great variety of complex targets were utilized and that the briefing by scope photographs was excellent. A photographic bomb scoring system provided assessment of a bombing performance and a basis for competition among the students.

Table 4

	A 315th Wing average	B 316th Wing average
Training days	15	34
Bomb runs per student	27	63
Main scope hours per student	26	61
Ground-speed error	12.5 knots	8.3 knots
Drift error	3.6°	2.9°
Circular probable error	3,000 ft	2,100 ft

Table 4 indicates the overall performance of the students for the 315th and 316th Wings.

Table 4 shows the value of the additional training on complex targets. In terms of bomb fall density, i.e., circular probable error squared, there is a factor 2:1 in the effectiveness of the operators of the two wings. This could be interpreted as meaning that one wing of "B" operators is worth two wings of "A" operators.

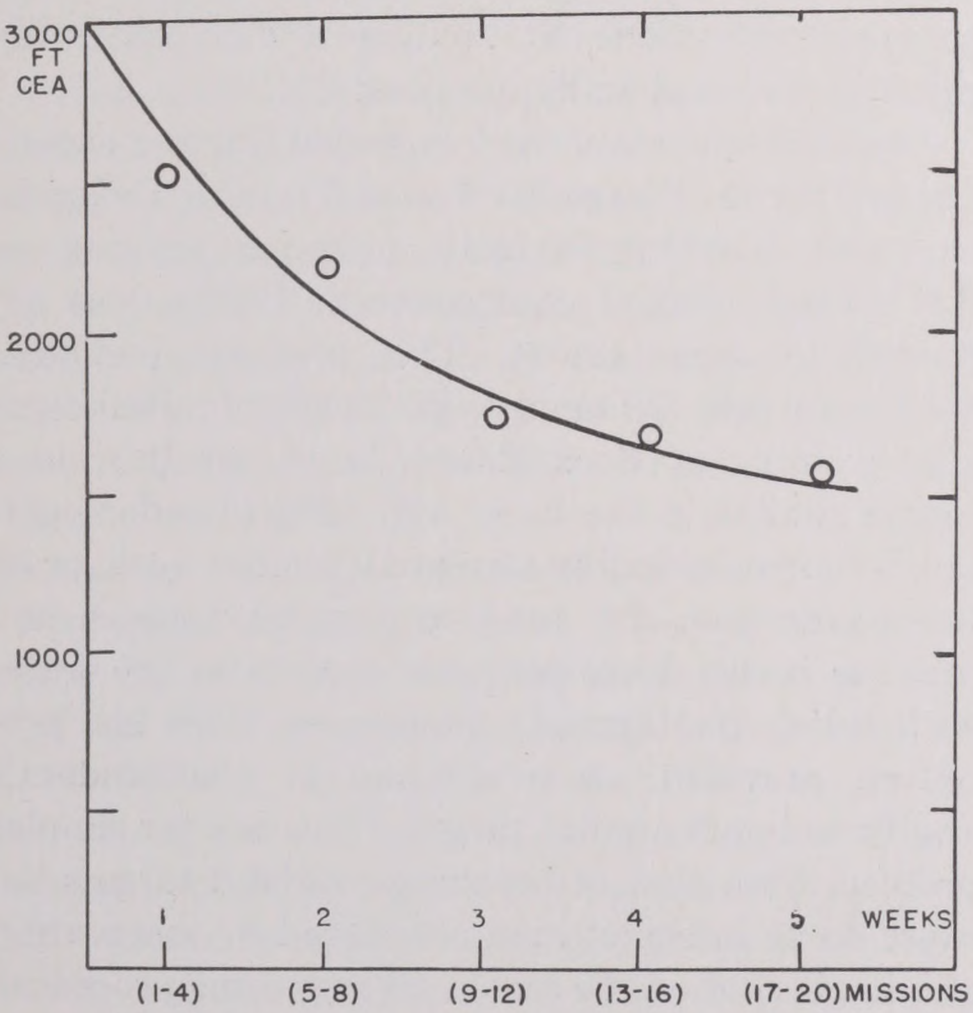


Figure 11. Progress curves, VAAF class 45E.

The progress curve indicating the improvement in bombing of one of the classes is shown in Figure 11. The scores are divided into five periods of four missions each and the average circular error in each period is plotted. The circular probable error of 3,000 ft at the beginning of the course was reduced to approximately 1,500 ft at the end of five weeks' training. In terms of bomb fall density the improvement is a factor of 4 and can be interpreted as meaning that one wing manned by these trained operators is four times as effective as a wing manned by operators without the extended training course. The cost of this training is of course insignificant compared with the cost of three additional B-29 groups.

13.2.6 Conclusion

Although the foregoing treatment of training is far from complete, it is hoped that some indication of the nature and importance of the problem has been given. In the opinion of the authors, the one factor that would have done most to improve the accuracy of radar blind bombing was increased skill (through training) of the operators. Whether the added time needed to produce this skill is more important than the early appearance of a large number of partially trained operators over the target is a matter for military tacticians to decide.

The alternative approach is to design equipment that is nearly automatic in operation. In this case, the required degree of skill could be obtained in the proverbial "three easy lessons." While this may be possible for any future military use of radar equipment, it is also true that the majority of important war weapons initially appear in crude form and depend heavily on operator skill for their performance. In view of this, an increased flexibility in establishing new organizations within the military framework is desired. It would then be possible to establish special groups whose main purpose would be to obtain the maximum use of any new weapon by all possible means, which would include an adequate training program.

Further information on specific training problems will be found in references 65–67, 73, and 74.

PART III

AIRCRAFT INTERCEPTION

[redacted]

Chapter 14

THE INTERCEPTION OF ENEMY AIRCRAFT

14.1 INTRODUCTION

14.1.1 The Aircraft Interception Problem

The interception of enemy aircraft is one of the major problems of modern warfare. From the most general point of view this subject includes the entire radar warning system, all intelligence operations for obtaining information on enemy air action, the strategic bombing of enemy aircraft factories, the antiaircraft artillery commands, barrage balloons, the fighter commands, and all armament for defense of bombers against enemy fighters. This section discusses only interception by fighter planes which use their own radar equipment at some stage in closing with the enemy planes. Although this *aircraft interception* [AI] equipment may be used under any conditions of poor visibility, it has been used primarily in night fighting.

Two main tactical methods are employed in bringing fighters into contact with enemy planes. These are *ground controlled interception* [GCI] and independent interception. In the GCI system, enemy planes are located by a complex surveillance network of which the major elements are ground radar systems. The fighter is sent up and establishes radio contact with a control center which guides him to within a few miles of the enemy. Final closing is made with the aid of the fighter plane's radar. *Ship-controlled interception* [SCI] in which carrier-based planes are guided into radar contact with enemy planes can be thought of as a special case of GCI control.

On the other hand, there is the independently operated plane which operates outside of GCI control. The principal use of this system is for "intruder" missions over enemy territory, for defense of a region in which a surveillance network is not yet established, or for defense against attackers flying so low or so fast that GCI is impractical.

Aircraft interception sets differ primarily from *aircraft to surface vessel* [ASV] sets in the requirement that relative elevation information must be supplied. If a scanning system is used, this means the addition of an added degree of freedom to the scanner motion to give elevation information as well as azimuth information. Thus, the AI scanner problem is more difficult than the ASV scanner problem (see Chapter 15). Considerable difficulties are also caused by sea and ground return obscuring the relatively weak aircraft signals.

A major problem in all types of AI work is the provision of adequate *identification of friend or foe* [IFF]. This is necessary both for the surveillance radar and for the interceptor plane. Especially in the case of blind firing by radar, it is desirable for the interceptor pilot to feel confident of the identification of his target as an enemy. An efficient IFF system can also save much effort which might be wasted in the interception of aircraft that turn out to be friendly.

Another important general problem is that of providing, in the design of both ground and airborne radars, a maximum effectiveness against countermeasures which the enemy may use, such as "window" or "carpet."

American radar sets designed primarily for AI use are: SCR-540 series (British Mark IV); SCR-520; SCR-720 series; AN/APG-1 and -2; AIA; AN/APS-6 and -6A; AN/APS-19 (in development at the close of World War II); and AN/APS-21 (in planning stage at the close of World War II). The AN/APG-3 and AN/APG-16 systems, designed for control of firing from bomber turrets, have radar search facilities and might be adapted to AI work.

14.1.2 Future Trends in AI

The future of air warfare is uncertain, but two facts stand out clearly. One is the great increase in speed of the attacking enemy planes; the other is the expected increased use of weapons similar to the German V-2 rocket. Improved AI tactics can probably cope with increased speeds in the range from 500 to 800 mph. However, AI as now understood cannot be expected to function successfully against weapons of the V-2 type.

The implications of higher speeds are many. Greater distances will be involved in an interception operation, and therefore greater radar range will be required. The necessity for detecting evasive action at the earliest possible moment means that higher scanning speeds must be used. The more pointed aerodynamic shapes of high-speed aircraft will make installation of AI scanners more difficult.

It is to be expected that increased use will be made of rockets by fighters. This means that the gunlaying radar associated with the AI system should have the necessary computers for rocket firing. Use of infrared techniques, especially in the closing stages, may be a very valuable adjunct to the radar. It may thus be possible, for example, to detect at an earlier stage the beginning of evasive action as indicated by banking of the hostile plane.

The *moving target indication* [MTI] technique now being developed for ground sets and for airborne detection of moving vehicles (Chapter 23) may provide an answer to the ground and sea clutter problem. At present such equipment costs too much in weight, but this objection does not appear to be insuperable. Considerable development will be required before the value of such techniques for AI will be established.

14.2 CONTROLLED INTERCEPTION

14.2.1 The Surveillance Network

A detailed discussion of the surveillance network for air defense cannot be given here, since the discussion is primarily concerned with airborne radar. The problem is essentially one of creating a vast organization for gathering information on enemy aircraft from radar, spotters, and intelligence services, and distribution of the information to antiaircraft and fighter commands. The fighter-direction centers direct the friendly fighters to a position where radar contact with the enemy is obtained. From then on the fighter is on his own, and it is with this aspect of the interception that we are primarily concerned. A discussion of AI tactics is given in Chapter 16.

For SCI work the available information is more limited, and hence the problem of defending a task force from enemy air attack is one of great difficulty. All airborne search radars of the Cadillac type, scouting planes, outlying fleet units, and the ship-based radars must supply information to the control centers which guide the defending carrier-based fighters.

14.2.2 The Radar Set for the Controlled Fighter

In World War II, controlled fighters have been both single- and multi-place planes. The Navy has favored single-place planes for carrier-based work, whereas in the defense of England the larger two-place planes were used.

The trend toward interceptor planes to give maximum speed will probably require a small fixed-gun plane whose one-man crew is both pilot and radar operator. The radar must therefore be extremely light, compact, and simple in operation. Since the GCI director guides the fighter to within a few miles of the enemy, the requirements on range are not so great as for an independent plane which has to seek its quarry. Navigation features and defensive radars such as tail warning are not essential, although they are desirable to relieve congestion and responsibility at the control center, and to allow pursuit of very fast or low-flying attackers. Chapter 15 presents a more detailed discussion of AI requirements and design problems.

In the class of sets suitable for controlled interception in single-place planes are the following systems: SCR-540; AIA; AN/APS-6; AN/APS-19. The AN/APG-3 and AN/APG-16 sets could probably be adapted to this use. Systems for controlled interception in two-place planes are the same as those listed in Section 14.3.2 for independent interceptors.

14.3 INDEPENDENT INTERCEPTION

14.3.1 The Tactical Problem

There is a definite need for interceptor planes which can go out on their own to seek out and shoot down enemy planes. Raids can be broken up over enemy territory while enemy bombers are climbing to altitude or getting into formation. Escort of friendly bombers over hostile territory at night is another function of this type of plane, as is air defense of territory in which a surveillance system for GCI control is not yet established.

14.3.2 The Radar for the Independent Interceptor

The best aircraft for intruder missions is a large fighter capable of relatively long-range missions. In general, there will be a separate radar operator as well as the pilot, comprising a two-man crew.

The radar installation must provide navigation and tail-warning functions as well as search, interception, and gunlaying. Since search is a major function, the radar must provide good range performance and wide angular coverage (at least 180 degrees forward). This means, of course, more power and greater mechanical complexity than in radars for single-place planes. Since there is a separate radar operator, greater complexity of data presentation is allowable.

The radar should provide both PPI presentation of the ground for navigational use and complete beacon facilities. The defensive tail-warning radar should be a separate set but should have its controls and display well integrated with the interception radar.

AI radar systems suitable for this type of work are the SCR-720, AN/APS-21, and to a limited extent the AN/APG-1 and -2 (which have inadequate search facilities).

A type of intruder mission in which the AI equipment can be greatly simplified is that in which the intruder picks out a particular enemy airfield and attempts to shoot down enemy planes while they are landing or taking off. For this purpose a range of only 1 or 2 miles is required, and there is little need for elevation information. Hence radars of the ASV type, such as the AN/APS-4, have been used for this work.

14.4 GUNLAYING PROBLEMS ASSOCIATED WITH AI RADAR

The object of every interception is to shoot down the enemy plane. Hence, means must be provided for aiming the fighter's guns, whether fixed or in a movable turret. Most AI interceptions in this war have been radar guided into visual contact, with the actual shooting achieved visually. Of the AI systems which saw service in World War II, some (SCR-540, -520, -720) have provided no radar gunlaying features; others (AIA, AN/APS-6) have noncomputing radar fire control. The fact that radar gunlaying has been little used in World War II does not mean that it will be unnecessary in future designs, but that it must be better and have more highly trained operators.

Part IV of this book is devoted to airborne fire-control systems, and the detailed discussion there covers most of the points of interest in AI work. Chapter 16 includes a discussion of the AI tactics which are used to bring the fighter into the most effective firing position.

For single-place controlled fighters, it will probably be adequate to have the radar scanner and presentation switched from search to gunlaying when the target is within range. Automatic tracking by means of a conical scan would then feed the necessary data to a spot-error indicator with range wings (G scope).

For the independent plane with separate radar operator, there are strong arguments for having a separate conical scanner for the gunlaying function. Thus, while the pilot is making the final approach, the radar operator can continue his search function. This would be particularly useful in the event that the automatic following were thrown off by evasive action.

Chapter 15

AI EQUIPMENT

15.1 DESIGN CONSIDERATIONS

15.1.1 Introduction

This chapter discusses the *aircraft interception* [AI] radar equipment carried in the interceptor aircraft. The design parameters influencing the performance of AI equipment, and the specific problems associated with AI equipment, together with examples of solutions of these problems as they have been met in practice, are presented. The emphasis will be on the components that are peculiar to the tactical function of AI radar equipment; consequently, the scan and the presentation are discussed in some detail.

The gunlaying feature of AI is omitted from several of the sets and is rarely used even in the sets that have it. Few pilots are willing to shoot blindly at a target that may prove friendly. Lack of faith in equipment for *identification of friend or foe* [IFF] has prevented the wide use of the blind firing facility in combat; the preference is to fire visually after visual identification. Accordingly, airborne radar fire-control facilities will not be discussed in this connection. (See however Part IV.)

15.1.2 Beamwidth

The width of an antenna beam as measured in the horizontal or azimuth plane is given in degrees by the approximate formula

$$\Theta = \frac{70\lambda}{D} \tag{1}$$

where λ and D are, respectively, the wavelength of the radiation and the horizontal dimension of the reflector. The same equation shows how the beamwidth as measured in elevation is influenced by the vertical dimension of the reflector. Narrow beams are obtained by the use of a short wavelength or a large antenna or both. The above formula agrees fairly well with measurements on most antennas.

In modern AI sets the beamwidth is 5 or 10 degrees. It is obvious that narrow beams are desirable as affording better accuracy and resolution. The value of narrow beams in the reduction of ground and sea clutter is discussed in Section 15.1.6. A K-band beam as narrow as 1 degree might make possible a crude display of the actual outline of the target airplane, so that the interceptor pilot could, by observing its banking, react sooner to its evasive tactics. The AI scanning problem is, however, so aggravated by such a narrow beam that its use has not been seriously planned.

15.1.3 Range Performance [21a]

Range Equation and Antenna Gain

The maximum range $R_{\max}$ at which a radar can detect a target depends on several quantities, including the wavelength, antenna gain, peak power P transmitted, the signal power $p_{\min}$ in the weakest discernible echo, and the effective cross section σ of the target. The received power is given by

$$p = \frac{PG^2\lambda^2\sigma}{(4\pi)^3R^4} \tag{2}$$

where G is the gain of the antenna, and R is the range to the target (see Section 7.2.2).

It follows that

$$R_{\max} = \left(\frac{PG^2\lambda^2\sigma}{(4\pi)^3p_{\min}}\right)^{\frac{1}{4}}. \tag{3}$$

In the above equations the quantities G and $p_{\min}$ depend on definite attributes of the radar system. The antenna gain G measures the directivity of the antenna; it is defined as the ratio of the energy density at the maximum of the beam to that from an equal source radiating isotropically. The gain of a pencil-beam antenna of area A is given by the formula

$$G = \frac{4\pi AF}{\lambda^2} \tag{4}$$

where F is a constant depending on the antenna design, and is approximately 0.5 for AI antennas.

Scanning Loss

The sensitivity of the radar as described by the power $p_{\min}$ in the minimum discernible signal depends on many factors, and a complete discussion is beyond the scope of the present book. Only the effect of scanning loss, recurrence frequency, and pulse duration will be considered. In discussing scanning loss we define $p'_{\min}$ as the minimum discernible signal when the beam is steadily trained (searchlighting) on the target. Then

$$p_{\min} = fp'_{\min} \tag{5}$$

where f is designated the scanning loss factor. A rough rule for approximating the scanning loss is

$$f = \left(\frac{1}{n}\right)^{\frac{1}{2}} \tag{6}$$

where n is the fraction of transmitted pulses of radiation which fall on the target. This holds approximately for scans which are completed in a time of about 6 seconds or less, as is the case with AI scans; it finds a certain justification both in the theory of measurements and in actual observation under controlled conditions. Six seconds represents a combined integration time of the observer and the persistence or afterglow of the cathode-ray screen.

For uniform scanning rates

$$n = \frac{\text{Solid angle } \Omega_1 \text{ of beam}}{\text{Solid angle } \Omega \text{ scanned}},$$

and therefore

$$f = \left(\frac{\Omega}{\Omega_1}\right)^{\frac{1}{2}}. \tag{7}$$

The foregoing discussion of scanning loss has been based on the tacit assumption that the signals appear at the same place on the screen in successive repetitions of the scan. If, as is generally the case in AI, this assumption fails to hold, a further loss in sensitivity of the radar results, involving perhaps a factor of 2 or more in minimum discernible signal. For purposes of comparing the performance of AI sets, however, this additional loss may be neglected as being of the same order of magnitude for all systems.

The problem of scanning loss has been treated by E. M. Purcell.[21a] He advances the point of view that, since both the target and the screen are scanned and pulsed repeatedly, it is profitable to consider not the scanning loss referred to the searchlighting condition, but rather a storage gain referred to the case of a radar which is trained on the target while emitting an isolated pulse.

If the scanning is nonuniform, the angular velocity ω of the beam must be taken into account, and in general ω is a function of two angular variables. Each scanning of the field is accomplished by traversing several lines of scan. If the lines are so close together that the beam falls on a given target while traversing several successive lines, the scanning loss is mitigated. An overlap factor k is therefore defined as the ratio of the beamwidth to the angular shift of the beam between lines. This is a function of the two angular variables. Let t_F denote the frame time (time for completely scanning the field once), ν_r the pulse recurrence frequency and Θ the beamwidth. Then for any beam direction, the number of pulses on the target in one frame is $\nu_r \Theta k/\omega$, the total number of pulses in one frame is $\nu_r t_F$ and we find, using equation (6),

$$f = (t_F\omega/\Theta k)^{\frac{1}{2}}. \tag{8}$$

Effect of Pulse Duration, Bandwidth, and Recurrence Frequency

The pulse duration of the transmitted energy has an indirect, though important, effect on the value of p'_{min}. The pulse duration τ (microseconds) fixes the optimum bandwidth of the receiver (megacycles) at about $1.2/\tau$. Thus, if the pulse duration is decreased for the sake of improved resolution of targets in range, the bandwidth must be increased. This gives a higher noise level and results in a decrease in signal discernibility. The resulting relation between the pulse duration and the minimum signal discernible while searchlighting is

$$p'_{\text{min}} \sim \frac{1}{\tau}. \tag{9}$$

The recurrence frequency also affects the value of p'_{min}. It is found [see equation (5)] that

$$p'_{\text{min}} \sim \left(\frac{1}{\nu_r}\right)^{\frac{1}{2}}. \tag{10}$$

Consolidation of Design-Parameter Effects

On substituting equations (4), (5), (9), and (10) into (3), we find the following dependence of the range performance of an AI radar upon design parameters:

$$R_{\text{max}} \sim \nu_r^{\frac{1}{8}}\left(\frac{P\tau}{f}\right)^{\frac{1}{4}}\left(\frac{A}{\lambda}\right)^{\frac{1}{2}}. \tag{11}$$

The value of f is calculated from equation (7) or (8). By equation (11) one may compare the range performance of AI radars and so arrive at an optimum design of new sets.

15.1.4 Angular Coverage and Frame Speed

The AI radars that have been in production have widely differing fields of view. It is important that the angular coverage for the search phase of AI should be ±90 degrees in azimuth (Section 16.2.2) and 20 degrees total in elevation, with the center adjustable by the operator from -10 to $+10$ degrees.[13] These requirements are for an interceptor on a free-lance mission, i.e., not under ground control. For controlled AI search the azimuth coverage need not be so great, and ±60 degrees is considered sufficient. In either case a frame time of 3 seconds is short enough.

The final interception phase of AI, after the enemy has begun evasive action, requires less range but wider angular coverage. The ±90 degrees figure for the azimuth coverage is still necessary, and the elevation coverage should be increased to at least a total of 30 degrees with the center adjustable from −15 to +45 degrees. The tactical situation in air combat changes so rapidly that the frame time should be reduced to 1 second.

The angular coverage and frame speed of specific AI radars are discussed in Section 15.2.1.

15.1.5 Navigation by AI Radar

It often happens that a radar is useful not only in its principal function but also in other functions as well. This is true of AI, which has proved of use in navigating en route to an intruder operation over enemy territory, and which is very valuable in the return flight to the airplane carrier or base of operations. This navigational facility is usually inferior to that of radars designed primarily for navigation, because the AI scans are primarily adapted for searching space rather than for detecting ground objects, and because the pencil beam from most AI antennas is less efficient in scanning the ground than is the fan beam of airborne navigational antennas.

In the detection of land masses or ships, the range performance is better than in the detection of individual aircraft. Therefore, particularly with high performance sets now under design, distant signals may appear on the second sweep. Various means have been proposed for eliminating this difficulty. One method is to vary the pulse recurrence frequency so that the unwanted echoes do not appear at the same place on the type B or the *plan position indicator* [PPI] display on successive sweeps.

The ability to interrogate beacons is of great value to an interceptor pilot returning to his base, and this ability is specified in practically all AI radars.

15.1.6 Ground and Sea Clutter

In AI operations it is observed that echoes from objects on the ground or from waves on the sea often seriously mask the echoes from the target airplane. In a certain sense, this surface clutter is a convenience in that by observing it on the screen the operator can estimate his altitude and the attitude of his airplane. Nevertheless, much effort has been expended in suppressing this generally bothersome effect.

In addition to the usual widely spread surface echoes, an altitude signal generally appears. This is an echo from the surface vertically below the airplane and is observed despite the fact that the beam is never directed vertically downward. It is caused by diffuse general radiation from the antenna and by downward reflections of the main beam by the radome. It may mask the signal from an airplane which is at a distance equal to the altitude of the interceptor.

Surface clutter may be reduced in several ways. One of the two most direct methods is to use short pulses; the other is to use a narrow beam. The efficacy of these methods will be understood from the fact that the signal from the target is in competition with the signal from an area on the surface.

The signal strength p^* from the surface is proportional to G^2 and to σ^*, the radar cross section of the surface area in question. Since the reflections from such things as trees and waves combine incoherently, this cross section is proportional to the area on the ground illuminated by the pulse which simultaneously strikes the target aircraft. This area is proportional to $R\Theta\tau$ at ranges large compared with the altitude.

Using equation (2) we find that

$$p^* \sim \frac{PG^2\lambda^2 R\Theta\tau}{R^4}. \tag{12}$$

In the competition between p [see equations (1) and (2)] and p^* it is desirable to minimize

$$\frac{p^*}{p} \sim \frac{R\Theta\tau}{\sigma} \sim \frac{R\lambda\tau}{\sigma D}. \tag{13}$$

There is a benefit from short pulses and from beams which are sharp in azimuth. For example, if the width of the reflector is doubled, the surface clutter is doubled but the signal strength from the target is quadrupled; the net result is advantageous. Clutter is not diminished in relation to the desired signals by increasing the vertical aperture of the antenna.

We have seen that range performance is improved by long pulses, but that surface clutter is reduced by short pulses. Also range performance is improved by a narrow beam, but the problems of scanning and scanner design are made more difficult by narrow beams. These factors must be kept in mind in choosing the optimum pulse duration and beamwidth.

Reduction of the altitude signal requires a reduction of the vertically downward radiation. With this in mind, the antenna should be designed to have side lobes as low as possible; 25 db below the beam intensity is a fairly good figure. A sheet-metal lining in the lower part of the radome has been found to help in SCR-720 installations by blocking the downward side lobes. If the scanner installation is poorly designed, the altitude signal may persist despite the choice of an antenna with low side lobes; this may happen if the radome reflects part of the beam energy downward or if a propeller or other part of the airplane is at any time illuminated by the scanning beam.

Surface clutter in the AN/APS-6 system is partly eliminated by cutting off the receiver during the time the scanner points below a certain elevation angle which can be controlled manually by the operator. This, of course, creates a blind volume below and in front of the airplane. A somewhat similar method proposed for the AN/APS-19 is to gate the receiver so that, when the beam is inclined downward, amplification takes place only until the time corresponding to the slant range to the ground. This means that the elevation angle and altitude information must be fed to a computer which can compute the product of the altitude by the cosecant of the depression angle of the beam, and that circuits must be provided to produce the computed gate length.

Various circuits have been developed to prevent saturation in the system resulting from clouds, sea, or land. A number of these circuits have been treated in detail as applied to the Cadillac system.[17] They will merely be listed here: (1) *sensitivity time control* [STC], (2) *instantaneous automatic gain control* [IAGC], (3) *fast time constant* [FTC] coupling between detector and video amplifier, (4) *detector balanced bias* [DBB] circuit.

As mentioned in Section 14.1, it is now possible to incorporate an *airborne moving target indicator* [AMTI] into an AI radar, enabling a display of objects which are moving in relation to the surface or to the interceptor while suppressing the signals from fixed surface objects. This technique is advantageous only on targets that are at a slant range exceeding the altitude of the interceptor.

15.1.7 AI Scans

The beam of the interceptor radar must be made to search a specified solid angle. This search may be made with a fan beam brushing over the field once every second or two, but such a scan would give data on only one of the two angular coordinates of the target. Such a scan would have a more favorable scanning loss value [see equation (7)] and a less favorable antenna area and gain than would a pencil-beam scan of several lines rapidly traversed. The range performance of the latter scan is better; equation (11) shows that the range advantage in this respect is a factor equaling in order of magnitude the ⅜ root of the number of lines in the complex scan. (Substitution of a pencil beam for a fan beam would multiply f by the square root of the number N of lines in the scan and would allow the gain or A to be increased by the factor N. The net alteration in maximum range is as stated.) The complex scans[8] are therefore preferred, both because they enable more definite locating of a target and because they allow earlier detection.

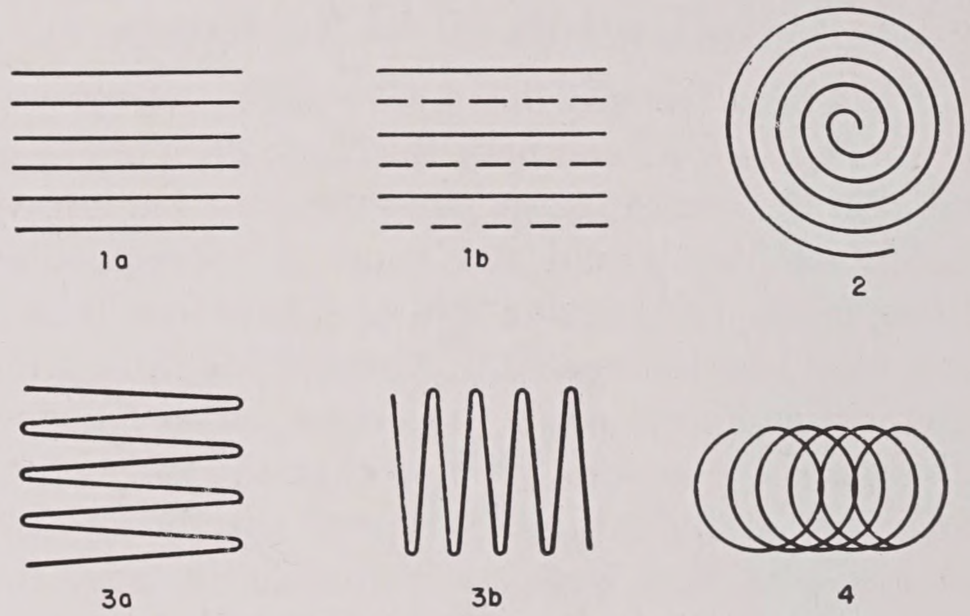


FIGURE 1. Types of AI scan.

Six complex scans have been considered for the AI function. These are shown schematically in Figure 1 and may be classified as:

1. Helical scan.
   a. Single reflector.
   b. Two reflectors back to back.
2. Spiral scan.
3. Wigwag scan.
   a. Rapid azimuth scan with slow elevation scan.
   b. Rapid elevation scan with slow azimuth scan.
4. Palmer scan (rapid conical scan with slow azimuth scan).

Of these scans, 2, 3b, and 4 involve rapid vertical motion of the beam. This is a bad feature as regards the B or PPI presentation, since it means that the same part of the screen where the target is observed is immediately and repeatedly filled with surface clutter. The much slower elevation motion of scans 1a, 1b, and 3a is free from this objection, and these scans are preferred.

The back-to-back helical scanner 1b is undesirable on the ground of excessive size, since the reflectors must be simultaneously tilted up (or down). It is easy to see that at the 60-degree elevation angle, which is the maximum required, the swept diameter of the antennas would have to be over two-thirds more than the reflector diameter, which is the swept diameter required for a single scanning reflector.

On the basis of the above discussion the choice of scan is narrowed to helical with a single reflector, or a horizontal wigwag scan. Further discussion of scans will be found below in the descriptions of specific AI systems.

15.1.8 Stabilization of AI Scanners

It has been thought that gyro-stabilization should be provided for AI scanners. Such a feature might be useful in the search phase, since then any banking of the interceptor would not cause a corresponding tilting of the rectangular field of scan. More important would be the benefit of stabilization during the interception phase when the target may be undertaking evasive action. Suppose that the interceptor radar, not stabilized, has a type C (azimuth-elevation) display and that, as is frequently true, the interceptor is pursuing behind and below the target. If now the target turns right, the interceptor pilot will turn right. This requires a steep right bank, which will put the azimuth of the target (referred to the tilted "vertical" axis of the interceptor scanner) to the left. The pilot will accordingly bank to the left, whereas he should be continuing his right bank. In this hypothetical situation, as in many others, there is confusion of the azimuth coordinate as referred to the banking airplane with the azimuth referred to a truly vertical axis. The elevation angle is subject to a similar confusion. This condition, possible only with an unstabilized radar, may be avoided by stabilizing either the scanner or the displayed data. Data stabilization in regard to roll would probably not be difficult or costly to apply to spirally scanning AI radars. The choice of method of stabilization will not be further discussed. Although in the foregoing the display was assumed to be a C scope, the argument is valid for B or PPI scopes as well. In the AN/APG-1 set (see Chapter 18) the radar artificial horizon reduces the need for stabilization.

15.1.9 AI Presentation

The indicator display presented by an AI radar [20a] is chosen first and foremost according as the interceptor does or does not carry a radar operator in addition to the pilot.

For one-place airplanes the double dot modification of a B scope has almost universally been used. The image of a single target is double, with the left-hand image indicating the range of the target and a theoretical centerline between the two dots indicating the azimuth. The right-hand image is above or below the other at an angle which varies as the target is above or below the axis of the interceptor. The cramped quarters of the cockpit have limited the diameter of the screen to 3 in., although a larger screen would be easier to read. As the interceptor closes on a target, the pilot changes successively from long-range to progressively shorter-range sweeps. However, it would seem that the changes provided should not be greater than a factor of about 2.5. Pilots have reported losing a target in changing from a 5-mile to a 1-mile sweep.

All AI sets designed for pilot operation provide blind-firing facility, consisting of a conical scan indicated on a G scope. This scope presents a single spot which qualitatively indicates the direction and magnitude of the error in aiming the axis of the conical scan. The target so indicated is the nearest one scanned, and if the two nearest targets are close together and at the same range the spot indicates, as it were, their center of gravity. Qualitatively the range is indicated on a G scope by wings electronically painted on either side of the spot, which grow as the interceptor closes.

AI for two-place airplanes may have not only a B scope for the operator but also a C scope, used after a target has been detected on the B scope. It is necessary for the operator to keep a range gate adjusted on the target in order to reduce the noise on the C scope. The position of the gate is controlled by a knob, allowing the operator to track the target in range; the tracking is made possible by range data read from the B scope. The pilot has a single scope which can be made type B or C at will. There is also provided for the pilot a range meter which simply repeats the position of the gate-control knob. In some cases the operator also needs a G scope for gun aiming.

15.2 AI SYSTEMS

15.2.1 American AI Radars

There have been designed in this country at least nine AI radars or radars adaptable to AI. These are SCR-520, SCR-540, SCR-720, AIA, AN/APS-4, AN/APS-6A, AN/APS-6, AN/APG-1, and AN/APG-2; all except the last two have been produced in quantity. In addition, three sets (AN/APS-19, AN/APG-3, and AN/APG-16, the last two of which are for bomber turret fire control) are in the stage of development and test, and one (AN/APS-21) is being planned.

The SCR-540 system, adapted from the British Mark IV AI radar, was manufactured by Western Electric Co. It has five fixed dipole antennas which do not scan, and operates at 193 mc. One of the antennas transmits about 800 pulses per second, of 1.3 μsec duration, diffusely in the forward direction, and the other four antennas receive the signals. The receiving antennas are directionally sensitive and are installed not quite parallel. They are connected in turn to the receiver and thus enable lobe switching. The display is a 3-in. double A scope with the base lines back to back (L scope) providing rough azimuth information on the target, as in the ASB radar. A second L scope, using the upper and lower antennas, provides elevation data.

Four of the sets mentioned were intended not only for interceptors but also for bombers. They are AN/APG-1, AN/APG-2, AN/APG-3, and AN/APG-16. AN/APG-1 and AN/APG-2, manufactured by Western Electric and General Electric, are similar in many respects. The former is described in Table 1. All four of these sets are discussed in Chapter 18. These systems are especially adaptable to the gunlaying function of aircraft interception. In this respect, the small size of the AN/APG-3 (General Electric) and AN/APG-16 (Sperry) gunlaying sets for bombers makes them especially appropriate.

The SCR-520 radar is of historical interest only as

TABLE 1. Characteristics of typical AI equipments.

	SCR 720	AN/APG–1	AN/APS–6	AN/APS–19	AN/APS–21[a]
Manufacturer	Western Electric	Western Electric	Westinghouse	Sperry	Westinghouse
Prod. date	1943	1943	1944	1946	?
Service	Army	Army	Navy	Navy	Navy
Frequency	3,000 mc	3,000 mc	9,375 mc	9,375 mc	9,375 mc
Search scan	Helical	Palmer	Spiral	Spiral[b]	?
Center (elev.)	Adjustable	$2\frac{1}{2}$°	Ahead	Ahead	– 15° to + 45°
Field (elev.)	– 30° to + 50°	30°	120°	130° or 30°	30°
Field (az.)	± 90°	165°	120°	130° or 30°	180°
Fast motion	6 c	4,000 rpm	20 c	20 c	?
Frame time (sec)	Typically 1	8	1	1 or $\frac{1}{4}$	1
Gunlaying scan	None	Conical	Conical	None	Separate radar
Center	. . .	– 10° to + 68°	Ahead	. . .	?
rpm	. . .	4,000	1,200	. . .	?
Antenna Diameter (in.)	29	27	$17\frac{1}{2}$	18	30
Beamwidth	10°	10°	5°	5° ($\csc^2$)	3.4°
Gain	340	310	1,100	1,100	2,400 ?
Peak power	100 – 150 kw	125 kw	40 kw	40 kw	250 kw
Radar pulses per sec	1,500	1,600	1,000, 2,000	2,000, 4,000	1,600
Radar pulse duration (μsec)	$\frac{3}{4}$	$\frac{3}{4}$	1, $\frac{1}{2}$	$\frac{1}{2}$, $\frac{1}{4}$	$\frac{3}{4}$, $\frac{1}{4}$
Beacon pulses per sec	375	400	500	500	400
Beacon pulse duration (μsec)	$2\frac{1}{4}$	$2\frac{1}{4}$	2	2	2
Operator's indication	5 in. B scope 5 in. C scope	5 in. B or C scope	Pilot operated	Pilot operated	7 in. PPI, off ctr 5 in. C scope
Pilot's AI indication	3 in. B or C scope and range meter	3 in. G scope, range meter[c]	3 in. B_0[d] or G scope	3 in. B, B_0[d] or V[e] scope	5 in. PPI 3 in. C scope
Radar sweeps	26,000 ft, 10, 20, 100 mi	5,000, 20,000 yd, 100 mi	1, 5, 25, 65 mi	1,500 yd, 2, 8, 20, 50, 100 mi	5 to 80 mi
Beacon sweep	100 mi	100 mi	100 mi	150 mi	160 mi
Range on fighter	5 to 8 mi	5 to 8 mi	3 to 4 mi	4 to 7 mi	15 to 20 mi
Gunlaying indication	None	Turret gun AGL	Fixed gun G scope	None	Separate radar
Weight (lb)	368	574	242	180 (inc bomb 40)	600 lb[f]
Power requirement	2.7 kw	3.6 kw	1.6 kw	1.5 kw	?

[a] Proposed system; question marks indicate undecided factors.
[b] Also has sector scan.
[c] Also overtaking meter and radar artificial horizon.
[d] Double dot modification.
[e] As in AN/APG-13B (*Vulture*); see Fig. 21, Chapter 20.
[f] Including the associated GL and tail warning radars.

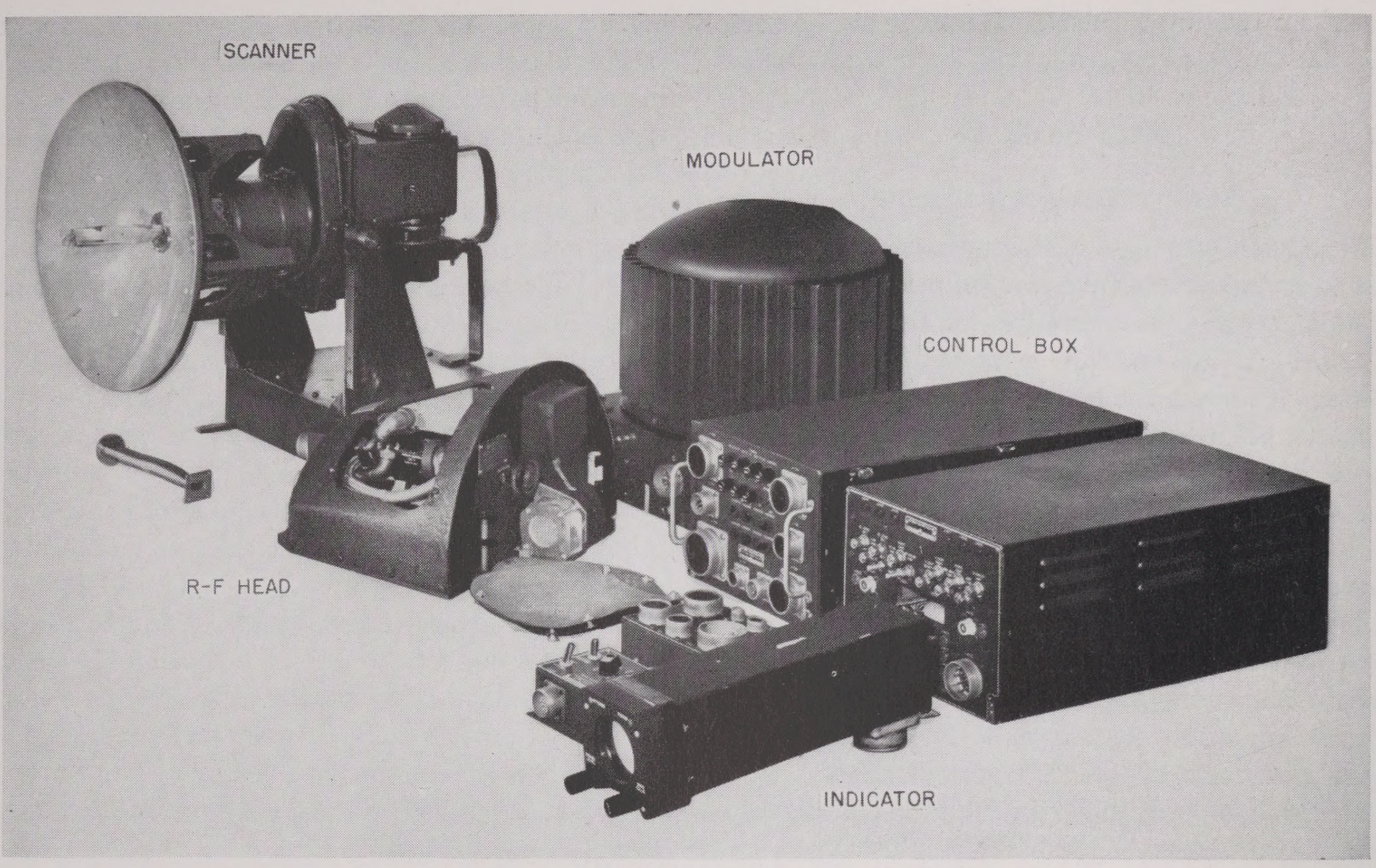


FIGURE 2. AN/APS-6 system components.

the direct ancestor of the lighter and more powerful SCR-720. Since these sets are rather similar, only the latter needs to be described. Its main attributes are displayed in Table 1.

In the AN/APS-4 radar manufactured by Western Electric the Navy has a widely used lightweight navigational radar with a sector scan indicated on a B scope. It was expected that optional automatic variation of the elevation angle, resulting in a four-line wigwag scan, would enable the set to serve efficiently in an AI capacity. This expectation has been only partly confirmed, although the set has been extensively used for AI missions against specific enemy airfields.

The AIA radar (manufactured by Sperry) for Navy night fighters was an early X band AI set affording gunlaying facility. It has been superseded by the somewhat similar AN/APS-6A and AN/APS-6 sets. The obsolescence of AIA was hastened by the undesirable long waveguide transmission line between the magnetron, packaged with the modulator in the fuselage, and the scanner mounted in a nacelle on the leading edge of the right wing. Troubles with installation, maintenance, attenuation, and the long-line effect were serious.

AN/APS-6A and AN/APS-6 avoid these difficulties by mounting the magnetron in the r-f head in the nacelle close behind the scanner. It is true that the pulse cable leading from the modulator in the fuselage to the r-f head is long, but the attendant disadvantages are slight. The only important difference between AN/APS-6A and AN/APS-6 is that the former was an interim set, which used the r-f head designed for AN/APS-3 until heads could be developed especially for AN/APS-6. Figure 2 is a photograph of the AN/APS-6 system.

During the latter part of World War II, a feeling arose that AN/APS-6 was too heavy for single-place airplanes and of too low a performance for two-place airplanes, that SCR-720 allowed too much surface clutter because of its great beamwidth, and that both sets were in many ways technically obsolescent. Therefore, two AI developments were initiated by the Navy, one toward an improved and lighter system for carrier-based single-place night fighters (AN/APS-19) and the other toward a high performance set for interceptors large enough to carry a radar operator (AN/APS-21). Completely different designs have resulted.

AN/APS-19 is designed for light weight and therefore only 4- to 7-mile range performance on such targets as enemy torpedo bombers. Since it is not intended for long-range search, its targets are perhaps almost as likely to be found above or below the axis of the airplane as to the right or left. Therefore, a 130-degree spiral scan is used. Since in AN/APS-6 the conical scan and the type G display give a field of coverage only about 15 degrees in diameter, the enemy has often eluded a pursuer by violent evasive tactics. Therefore, conical scan is not used in AN/-APS-19, but there is specified instead a supplementary spiral scan of very fast frame time and 30-degree field. In order to improve surface search, land mapping and beacon performance, a sector scan is also incorporated. During this scan the antenna feed is automatically altered so as to produce a fan beam instead of the usual pencil beam, thus enabling detection of near as well as distant objects on the surface.

A possible set of requirements for the proposed high performance AI set, AN/APS-21, has been prepared by the Radiation Laboratory.[13] The data under this system in Table 1 are taken from this source. The desired range performance will be obtained by higher power and gain and by increased receiver sensitivity. The scanning problem is extremely difficult in view of the short frame time, great angular coverage, and narrow beam.

The two scans most seriously considered for AN/-APS-21 are, as mentioned in Section 15.1.7, the helical scan and the horizontal wigwag scan of Figure 1. The choice of scan for AN/APS-21 is not easy. The scanning requirement for interception is more severe than for search, and will probably fix the choice of scanner type. Supposing the 30-degree elevation zone to be scanned by 12 horizontal lines at 2.5 degrees spacing, a helical scanner would have to rotate at 720 rpm or a wigwag scanner would have to oscillate at 360 cycles per minute in order to achieve a 1-sec frame time. Assuming a pulse recurrence frequency of 1,600 per sec and using equation (7), we calculate the scanning loss factor to be 30.5 for the helical scanner or 27.1 for the wigwag type. The latter has a very slight advantage.

A wigwag scanner design [12] has been developed which is adaptable to the requirement of AN/APS-21. This uses an elastic restoring torque on the vertical wigwag axis of the antenna, of a magnitude so chosen that the antenna oscillates like the balance wheel of a watch at the desired frequency. The oscillation of this scanner is sustained by an electric motor; the amplitude may be set by the operator at will, enabling a mitigation of the scanning loss within a narrowed sector if desired. By clutching a flywheel to the motor shaft it could be made possible for the operator to have a slower scan rate at will.

A seven-inch PPI presentation was recommended for the AN/APS-21. The most efficient use of the screen would require the center of the display to be offset downward to about one-third the radius of the screen; below this point the screen would be blank.

15.2.2 AI Maintenance

Introduction

A more complete discussion of the problem of radar maintenance is given in Section 5.1. Although it was written for ASV radar systems, all the information included in it is pertinent and directly applicable to AI radar equipment. The design and installation of AI systems, however, accentuate some of the aspects of the radar maintenance problem. Thus, for example, the mounting of the r-f head in an AN/APS-6 or AN/APS-6A system close behind the scanner required that very careful consideration be given to the design of the directional coupler for these systems so that it could be suitably installed and its output made readily available for test purposes. Unfortunately the design, installation, and dispatch of AN/APS-6 and AN/APS-6A systems to active theaters was accomplished prior to the design of a satisfactory directional coupler. It was necessary, therefore, to design a directional coupler for retroactive installation.

Special AI Test Equipment

Since the scanner and r-f head of an AN/APS-6 system, for example, are mounted in the wing nacelle of a carrier-based night fighter and since the wings are folded back during any maintenance, it is necessary to install the test panel in the wing nacelle near the junction box, and in such a manner that all the test points are readily accessible. The test points to be included are discussed in Section 5.1.4. A control for a movable range mark should be provided on the test panel, if the test video contains such a range mark for echo box measurements. Although these remarks pertain primarily to a system of the AN/-APS-6 type installed in a Navy night fighter they can be easily generalized to include other types of AI systems and other types of installations.

Three items of test equipment are rather special to some AI systems (although two of them, or suitable modifications, are used with other radar equipments);

they are power absorption cone, boresighting equipment, and scanner balancer.

The power absorption cone (or screen) is designed to absorb radiated energy from the antenna to prevent interference with nearby systems and reflections from nearby objects. This equipment is necessary during tests inside a hangar.

Boresighting is the method of aligning the guns with the scanner, for those systems which have a gunlaying scan and indication, such as the AN/APS-6, -6A, and -19. The SCR-720 type of system has no gunlaying scan and indication; consequently, no boresighting is done for the systems of this type. The two methods of accomplishing the alignment of the guns with the scanner are optical and radar. Up to the end of the hostilities of World War II the optical method was used with AN/APS-6 systems, since no suitable radar method had yet been developed. Experience with the radar boresighting of other systems [14, 15] indicated, however, that the accuracies to be attained would surpass those of the optical method.

The following is a description of the optical method of boresighting the AN/APS-6 system. The aircraft is blocked up in a horizontal position on jacks at a standard position in front of the hangar wall on which are standard marks at which the guns are pointed. A boresighting telescope, of the diagonal vision type, is fastened to the yoke of the antenna by means of a right angle bracket. The telescope is pointed at the boresighting chart on the hangar wall, and is rotated about the axis of scan by manually rotating the yoke upon which it is mounted. The center of rotation, as determined by the telescope, is taken as the radar boresight point. The telescope need not be clamped accurately in position on the yoke, since misalignments cancel during the rotation process; it is clamped rigidly, however. The two sources of error in this method are: (1) radar reflections from the fuselage or other parts of the plane are neglected; and (2) the boresighting tool is mounted on the yoke which drives the dish rather than on the dish itself (the dish is allowed to point in any random position during boresighting). If, during conical scan, the dish does not describe a circle about an axis coincident with that of the yoke, the boresight is in error, particularly if the dynamic orbit of the dish is not the same as the quasi-static orbit of the dish.

Thus, a telescope of the diagonal vision type, a right angle bracket, and the boresighting chart are necessary items of test equipment for these systems. Since the optical method is used it is essential that the radome be easily and conveniently removable.

A scanner balancer is a machine which measures and analyzes vibration in terms of amount and location of weight to be added to produce satisfactory operation. It is used for systems having spiral and conical scanners. The *Gisholt scanner balancer machine* (GGJ-10AEH) was especially designed for systems such as the AIA, AN/APS-6, AN/APS-6A and AN/APS-19; it has been used at major repair depots.

15.2.3 The Installation of AI Equipment

This discussion involves chiefly the installation of the scanner, which alone presents problems peculiar to AI. In single-engine night fighters the AI scanner is installed in a nacelle well outboard on the leading edge of the right wing. This location is chosen in order to avoid radar interference from the propeller and in order to allow unobstructed vision to the pilot as he circles for a landing. Installations of this sort that have been made in quantity are AIA, AN/APS-6A, and AN/APS-6 in F4U or F6F airplanes. The radar scanner is installed inside the nose of two-engine night fighters, such as the F7F and P-61. Almost the entire AN/APS-19 system may be mounted in a "bomb" under the right wing of single-engine airplanes; the nose of the bomb is the radome. AN/APS-21 is intended for use in two-engine airplanes with the scanner located in the nose.

Any scanner providing a gunlaying facility must be harmonized with the guns. The process of harmonization or boresighting is simply the correct adjustment of the angular position of the scanner base, and means for this adjustment are provided in the scanner design. The tests for correct adjustment were discussed in Section 15.2.2.

Problems concerning the r-f transmission line have been discussed above in connection with AIA. An additional difficulty arises from the shock mounting of the r-f head and the rigid mounting of the scanner. Their relative motion necessitates flexibility in the short length of transmission line that joins them.

The radome of AI radar must be designed with unusual care. First, it must be good aerodynamically since it is on a critical part of the exterior of a very high performance airplane. Second, it must be of the lowest possible reflectivity. A reason for this, peculiar to AI, is that reflections set up standing waves in the transmission line which, considering the rapidity of the scan, vary the frequency of the magnetron too rapidly for the automatic frequency control to follow; furthermore, reflections from the radome downward to the ground cause an increase in surface clutter and the altitude signal, which are especially unwelcome in AI. And third, the radome design must be such as to prevent the entrance of rain or spray, whether the airplane is in flight or on the flight deck with its wings folded. Dew or a thin film of water may cause great reflection and attenuation. Improper mounting can allow several quarts of rain water to collect in a radome installed on a wing whose leading edge points downward when folded.

It is imperative that ample tests be conducted to make sure that the antenna pattern is satisfactory. In the final stages of the testing and development, the scanner must be mounted in the proposed radome on a mockup of the intended airplane, and the time schedule must make provision for alterations to the antenna, the radome, the airplane or even to all three.

An installation feature in the cockpit of an AI airplane, which has been strongly advocated in England but thus far not used in this country, is windscreen projection. The cathode-ray tube is so mounted that the pilot readily sees its reflection in the flat window surface of the canopy before him.

In the design of AI equipment, as in all airborne radar, it is important that the closest cooperation be encouraged by the interested service among the electronic development agency, the equipment manufacturer, and the aircraft manufacturer. The last mentioned has too often been left in ignorance of the space and other requirements of the radar, and a poor installation has resulted.

Chapter 16

AIRCRAFT INTERCEPTION TACTICS

16.1 EARLY TECHNIQUES

16.1.1 Preradar Techniques

The earliest techniques involving night fighters in the defense of territory against attacking enemy bombers utilized ground-based early warning systems, searchlights, and day fighters operating at night. The approach of the enemy bomber was detected by the early warning system which determined the course of the bombers. As the bomber approached the target, it was illuminated by the intersection of the beams from three searchlights (manual or radar controlled) which tracked it. When the approaching bomber was detected, fighter aircraft were alerted and directed to the searchlight area, which was then patrolled at an altitude above that of the attacking bomber. The fighter attacked the bomber from above and on the tail as soon as an interception by three of the searchlights had been made. The fighter had the advantage of essentially daylight visibility; the bomber gunner, on the other hand, had impaired visibility as a result of the glare of the searchlight beams. The use of this technique permitted the operation of ordinary day fighters at night.

Such tactics were only adequate for dealing with small raids under conditions of good visibility. Furthermore, concentrations of searchlights were only practicable near important targets, so that this defensive operation could take place only after the bombers had reached their objective. The need for radar controlled and equipped night fighters to intercept the enemy before reaching his target was recognized at an early stage of World War II, and considerable effort was expended on the development of such equipment.

16.1.2 Radar Techniques

The advent and extensive use of *ground controlled interception* [GCI] and the development of airborne radar systems for the detection of other aircraft resulted in great modification of night fighting tactics. The radar-equipped night fighters were alerted, directed by the GCI to an altitude above that of the raiding bomber, and then vectored (by the GCI) to the bomber. The GCI relinquished direction of the fighter to the radar operator in the interceptor when the target was within the radar range of the fighter. The radar operator then directed the pilot to within a few hundred yards of the bomber, at an overtaking speed of 10 to 30 miles per hour, and to a position above or below (depending upon such factors as light conditions and clouds), and to one side of the bomber. After establishment of visual contact the pilot opened fire at the appropriate range and bearing.

Long wave radar (approximately 200 mc) sets were the earliest *aircraft interception* [AI] equipments used in the manner described above. These sets, developed by the British, gradually evolved into the Mark IV AI system (U. S. version: SCR-540). Later sets used shorter wavelengths (10 cm and 3 cm) and higher power, and some provided for blind firing. The tabulation of AI radars in Chapter 15 summarizes the characteristics of these later sets. Tactics were modified to meet the characteristics of each new type of set.

16.2 GENERAL ANALYSIS OF AI TACTICS

16.2.1 Introduction

An analysis of AI tactics should have two major objects: first, to examine the tactical requirements with the object of making the most effective use of available equipment and second, to arrive at a sufficiently broad understanding of the general problem that more effective equipment can be designed. Although the number of possible tactical situations is very large from the theoretical point of view, experience in World War II showed that the important general situations encountered were GCI controlled missions, free-lance search missions, and free-lance marauder missions against specific targets.

GCI Controlled Missions

With GCI techniques in use at the close of World War II the fighter could be directed from the ground into almost certain radar contact with the enemy. Failures to establish contact could usually be attributed to failures in the radar equipment or in communication. Furthermore, GCI could bring the fighter into contact on a favorable relative course, so that complicated maneuvers were not necessary for getting into firing position, except in so far as these were necessitated by evasive action of the enemy.

FREE-LANCE SEARCH MISSIONS

The independent mission in which the fighter has no prior information concerning the possible location of enemy planes is another important tactical situation. Two distinct stages are apparent — search and interception; each stage requires separate discussion in an analysis of tactics. The interception stage in this situation differs from GCI interception in that a favorable relative course cannot be assumed. The most probable course of an enemy plane when radar contact is established is directly opposite from the fighter's course, the condition least favorable for interception.

FREE-LANCE MARAUDING MISSIONS

In a free-lance mission against a known point of enemy air concentration such as an enemy airfield, search is relatively simple. The interception conditions, however, vary considerably with the exact situation, but in general a favorable relative course cannot be counted on. These night missions against enemy airfields were dangerous because of the necessity for maneuvering at low altitude and the accuracy of enemy ground fire. Many such missions were, however, successful in World War II.

These three tactical situations will be discussed in terms of two probability functions: the radar contact probability, which defines the probability of establishing radar contact with an enemy; and the interception probability, which determines the probability that once radar contact is established, the fighter can be brought into firing position. The probability of successful firing will not be discussed.

Since in GCI controlled missions the fighter can be directed into almost certain radar contact with an enemy, the radar contact probability is essentially unity; consequently, it is not discussed further.

16.2.2 Radar Contact Probability

In studying radar contact probability on a free-lance search mission against an unknown distribution of enemy targets, certain simplifying assumptions can be made without seriously limiting the applicability of the results. It will be assumed, first of all, that the maximum range of the radar is large compared to the altitude range in which targets are expected. This means that the coverage can be considered to be cylindrical, and the problem is essentially reduced to two dimensions. Secondly, it will be assumed that the targets are moving at random, and that the average density of targets is uniform in the region considered. The fighter will be assumed to be moving with constant speed in a fixed direction.

The analysis in the present section is largely based on that given by Dr. H. M. James[4] in a report discussing the contact probability for a bomber flying through a uniformly patrolled region. The results derived in this report apply equally to the discussion of a fighter flying through a random distribution of bombers.

A number of important results established in this report are summarized below with all derivations omitted.

1. Most contacts will be made in the forward hemisphere. If u is the speed of the fighter and v the speed of the enemy aircraft, the per cent of contacts made in the forward hemisphere is given as a function of v/u in Table 1. It is assumed that the fighter's radar has a 360-degree coverage.

TABLE 1. Per cent of forward contacts as a function of speed ratio (Assuming 360-degree coverage).

$\frac{v}{u}$	Per cent forward contacts
0.8	92.8
0.9	91.0
1.0	89.2
1.1	87.2
1.2	84.8

This means that little is gained for AI work by scanning the rear hemisphere, except to provide some tail-warning against enemy fighters.

2. Aircraft coming into radar contact are most likely to have a relative course angle of 180 degrees with respect to the fighter. The distribution of these encounters for 30-degree intervals in the case of an AI set viewing only the forward hemisphere is given in Table 2.

TABLE 2. Distribution of encounters according to relative course.

Relative course angle (degrees)	Fraction of encounters having angle in this range (per cent)
0–30	2.2
30–60	7.8
60–90	14.4
90–120	20.8
120–150	26.0
150–180	28.8

Thus 24.4 per cent will be heading away from the fighter and 75.6 per cent toward the fighter. These results are important in determining subsequent tactics. The independent interceptor must expect that most contacts will be made at large course angles, which presents a difficult problem because of the difficulty of turning into a homing course without losing the enemy. This problem will be further discussed in Section 16.2.3.

3. When an enemy plane is detected at extreme range, its most probable course is directly toward the observer. The nearer the bearing is to straight ahead, the greater is this probability. Thus, if any action is to be taken while an enemy is still at extreme range, before his course is determined, the choice of tactics should be made on the assumption that the enemy is proceeding directly toward the observer.

Radar contact probability for a free-lance marauding mission against a known point of enemy air concentration is in general higher than for free-lance search missions. For, in marauder missions, the radar contact probability is dependent largely upon the ability to navigate to a fixed target where the density of enemy aircraft is expected to be higher.

16.2.3 Probability of Interception

Interception probability after radar contact is established is discussed here for a fixed-gun fighter only, since practically all interceptor aircraft used in World War II were of this type. The standard tactical procedure for this type of fighter was to approach the enemy from behind on an approximately parallel course. Interceptions are more difficult if the enemy is initially on an opposite course from the fighter when radar contact is established (as is most probable in the random search case, Section 16.2.2) than if accurate GCI has brought the fighter into a parallel course behind the enemy.

James [2] has given a detailed theoretical treatment of the dependence of interception probabilities on the relevant factors involved. He makes the following assumptions: (1) the two aircraft are at the same altitude (thus reducing the problem to two dimensions); (2) the fighter pilot keeps his plane directed at the target whenever possible (homing tactics); (3) maximum rate of turn is used to bring the target dead ahead; (4) the approach is made at constant airspeed; (5) loss is considered to occur if the target gets out of the range of vision of the fighter. Some of the more important results of this treatment are included in the following discussion. Derivation of the results is not within the scope of this book.

Effect of Radar Range

For accurate GCI work the radar range need only be sufficiently large to ensure contact while under ground control. This means that the radar range must be greater than the GCI error radius. Greater range of the fighter radar will, of course, decrease the time which GCI must spend on a given fighter, and hence increase the traffic-handling ability of a given ground control station. This may be extremely important in the event of large raids.

For independent interceptions, the probability of successful interception increases with the range of the radar. Furthermore, the rate of increase of interception probability with range is also an increasing function of range. The increase with range is most rapid when the two planes are initially approaching each other.

The greater the angle of radar vision, the more valuable will be an increase in range. On the other hand, if the available rate of turn is increased, less stress need be laid on range.

Speed Advantage

Too great a speed advantage, especially in the late stages of pursuit, leads to a decrease in interception probability. As the target is approached, speed advantage should be reduced to at most 20 per cent or preferably 10 per cent.

As the radar range is decreased, there is increased danger of losing the target if the speed advantage is too great.

Available Rate of Turn

For GCI interception, the rate of turn is principally important in those phases of the pursuit when the target is taking evasive action.

For independent interceptions, where the initial relative course angle can be expected to be large, the probability of a successful interception increases rapidly with the maximum rate of turn of the fighter. In night fighting there is a tendency for pilots to restrict themselves to relatively low turning rates; this should be avoided so far as possible. However, the advantage of increased rate of turn falls off rapidly as radar range is increased.

Angle of Radar Vision

For GCI interceptions a large angle of vision is valuable both in ensuring radar contact, and in following evasive action.

Wide-angle vision is even more important in the case of independent interceptions where unfavorable initial courses can be expected. Increase in angle beyond 180 degrees is probably not worth the added weight required, but increase from 120 to 180 degrees greatly improves the chance of interception.

Persistence of Pursuit After Target Disappearance

The target sometimes will go out of the range of vision (in angle) of the pursuer at some stage of the pursuit. This situation is most likely when a small rate of turn is available. In this case it is very important that the pursuer not give up, but continue in his circular course (at maximum rate of turn). Such persistence may add as much as 30 per cent to the probability of interception.

The greater the available radar range, the more important is this persistence. The greater the available rate of turn, the smaller will be the increase in target range during the time that the target is out of sight.

16.3 SPECIAL PROBLEMS IN AI TACTICS

In Section 16.2 AI tactics were discussed from a general point of view. In this section we will discuss the effect of certain special factors on tactics.

16.3.1 Firing Methods

Once a fighter is on the tail of an enemy aircraft either visual firing or blind firing (if the radar is equipped with this facility) may be used. Blind firing has several advantages over visual firing: (1) the range information is much better than any visual estimate, especially when made at night; (2) radar firing can begin at greater ranges, thus reducing the danger of detection and defensive fire by the bomber; (3) the total time of approach is decreased; (4) the angle about the tail of the enemy aircraft, in which night fighters are expected at any stage during their approach, is increased; (5) the turning rates required to keep the night fighter's sights on the bomber are decreased. Visual firing, on the other hand, has the big advantage of better target identification, but this factor is much less vital if adequate radar identification equipment is available.

AI radars, such as the AN/APS-6, which have blind firing directed by a conical scan, restrict the final closing operation to a direct tail chase. The condition that the target be centered on the G scope, and remain centered, is that the line of the fixed guns of the fighter (and thus of the conical scan axis) remains pointed at the target. Enemy evasive action is very likely to be successful against this type of installation.

Night fighters equipped with turrets such as originally planned for the P-61 would, of course, allow much more flexible tactics in the closing stages of pursuit than were possible with fixed gun fighters. Automatic following, such as provided by the AN/APG-1 system, allows easier following of evasive action than is the case with nontracking radar sets.

16.3.2 Nature of Target

Tactics should be planned with all possible knowledge of the enemy target in mind. The most important factors to be considered are: the coverage and range of defensive radars (such as tail-warning); the nature and extent of enemy defensive fire power; the speed of the enemy planes; and the probable tactics which the enemy will use in avoiding pursuit. Prior knowledge of any of these factors will affect both GCI and AI techniques.

The tactics employed in combating missiles, of the guided or unguided type, depends upon the type of missile. Missiles such as the German V-1 buzz-bomb are easily visible at night, so that radar-equipped night fighters are not required. The tactic adopted in this case consisted of cruising at an altitude several thousand feet higher than that at which the V-1's were flying; when a buzz-bomb was detected, the fighter dived toward the missile, thereby obtaining a speed advantage.

16.3.3 Evasive Action

The evasive action frequently employed by bombers is to change altitude and course (by 5 or 10 degrees) at intervals of 1 to 2 minutes. Thus, the weaving character of the target course may cause difficulty for a night fighter in the final stages of approach. An evasive maneuver very difficult for the night fighter to follow is a sudden sharp turn through 360 degrees by the bomber to throw the night fighter off the bomber's tail. This maneuver is especially

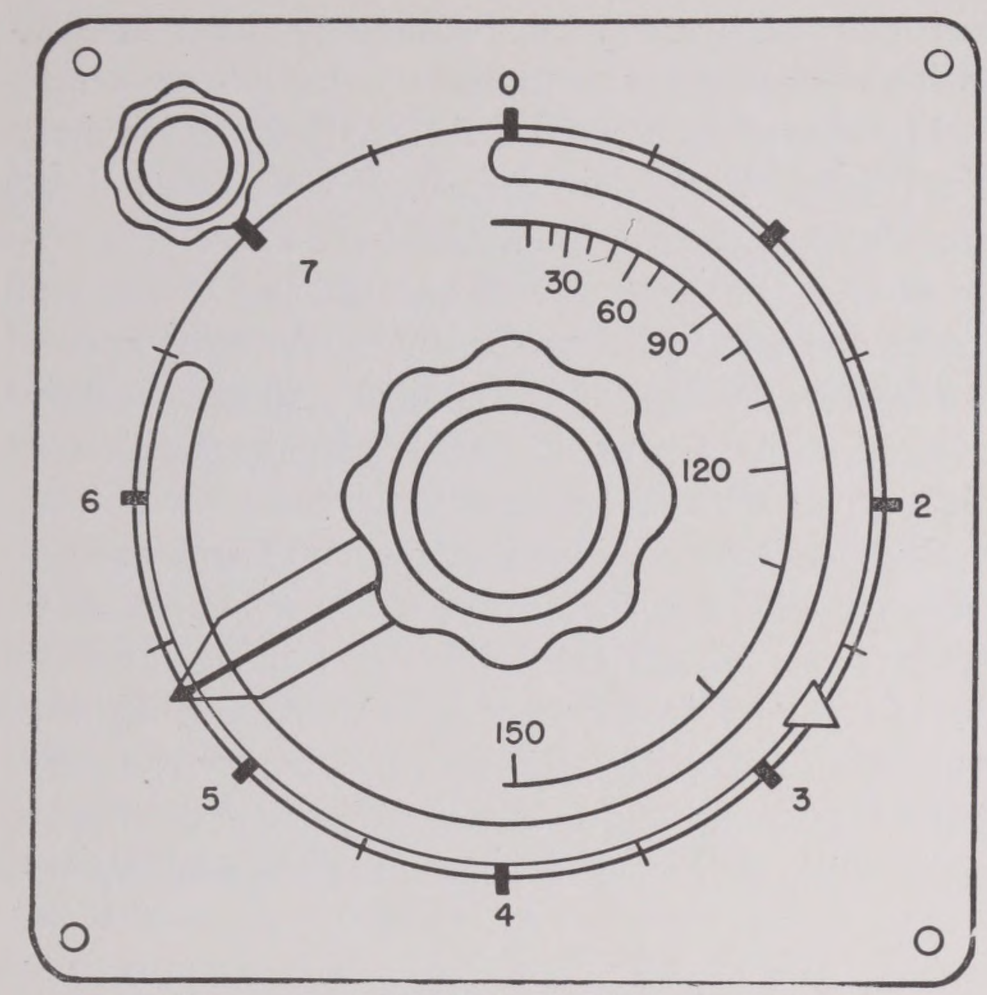


Figure 1. Simple form of range clock.

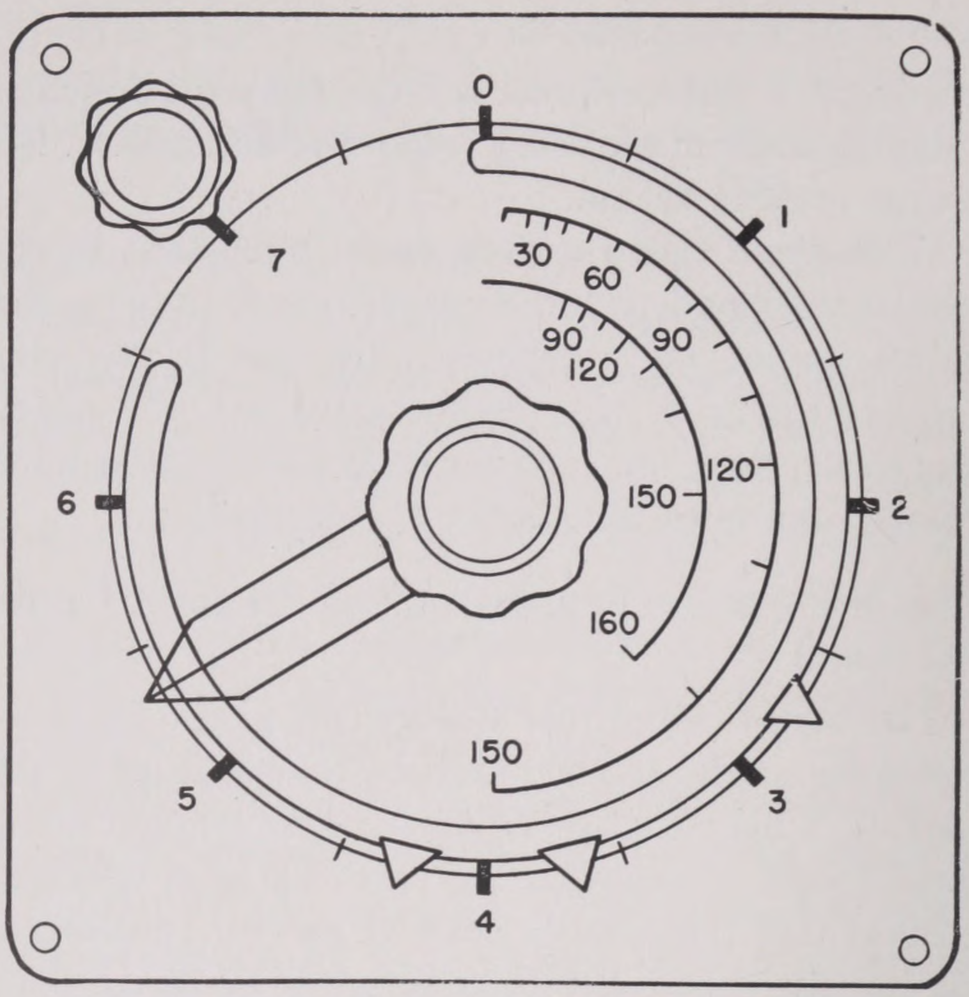


Figure 2. Standard range clock.

difficult to follow if the fighter is close to the bomber at the time the bomber initiates this evasive action. Another maneuver which is very effective is to peel off in a steep dive to left or right. In general, however, large angle turns will not be encountered by the defending fighter, because a bomber employing such tactics would require extra fuel at the expense of bomb load.

16.3.4 Effect of Ground or Sea Clutter and Countermeasures

The quarry can be lost during the approach because of disappearance in the altitude signal, disappearance in the ground or sea clutter, or the effects of window or chaff. A discussion of the altitude signal and sea and ground clutter is given in Section 15.1.6. References 9 and 10 contain a detailed discussion of sea return and altitude effects in the AN/APS-6 system, with particular reference as to how the tactics might be affected for this type of system.

Window or chaff is sometimes used to protect attacking bombers against defending interceptors. The object of using window is to present the equivalent of a large number of reflecting dipoles so as to effectively jam the GCI and AI radars protecting the territory under attack. Window is dropped from several of the attacking aircraft in an attempt to confuse the GCI and AI radars. Narrow beam and short pulse durations in the radar systems are the most effective means of penetrating this interference, although it is possible, in principle at least, to drop sufficient window to cause loss of the target altogether.

16.4 THE RANGE CLOCK

In any interception the night fighter must get onto the course of the bomber and convert the approach to a tail chase in the most efficient manner possible. James[6] has devised a *range clock* which enables a night fighter to get on the course of the target with a minimum number of radar observations. The use of the range clock reduces the approach to a target to the following steps: (1) turning until the target is dead ahead, (2) flying a straight course at a standard airspeed, and (3) executing a single turn at a standard rate through an angle determined in advance.

A range clock, in its simplest form (Figure 1), consists of a moving hand, a marker having a fixed position during each run, and two scales on the dial face. The outer scale is a range scale calibrated in miles; the inner scale is calibrated in degrees and indicates the point at which the turn is to start. For application to large angle interceptions two additional markers are added to the range clock, producing the so-called *standard range clock* (Figure 2). These two additional markers allow the radar operator to determine whether the interception is nearly a head-on interception, and provide a method of hand lingsuch interceptions.

The operation of the simple range clock is begun with both hand and marker in the zero position. When the starting knob (upper left corner) is pulled out the hand can be set to any range indicated on the outer scale. The marker is automatically set at one-half of this range.

Referring to Figure 3 we will assume that the fighter is at P after having turned toward the target which is now dead ahead at range PT. The clock is set at range PT and started; the pilot flies a straight course (P to T). As described in James' report, "the hand of the range clock will move toward smaller ranges at a rate equal to the standard airspeed agreed on in advance for use in these approaches; thus it will indicate at any instant the distance still to be traversed before the point T is reached.

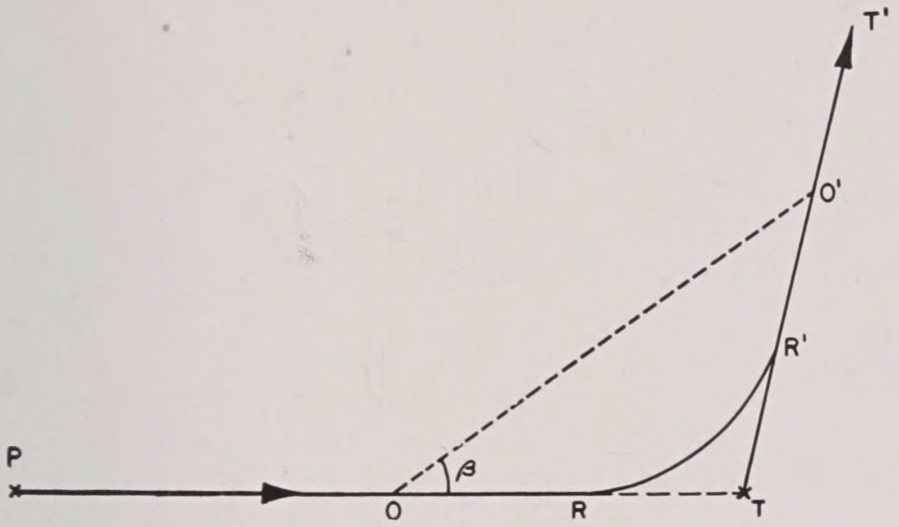


FIGURE 3. Approach of fighter to target using range clock procedure.

"When the clock is started the marker remains fixed. When the hand has reached the marker the pursuing plane will be at point O (Figure 3), halfway to point T, while the target will be at O', nearly an equal distance from T. At this moment the radar operator will observe the bearing angle β to the target.

"By doubling the angle β the radar operator can determine the angle between the courses of the two planes, which is the angle through which the pursuing ship must turn. He should then at once pass this information to the pilot."

Doubling the bearing angle to obtain the angle between the courses is exact if the speeds of the target and pursuer are equal; if not, correction may have to be made for greater precision.

To determine the time at which this turn should be begun, the radar operator will now refer to the inner scale. This is calibrated in terms of the angle between the courses of the planes; the calibration depends on the rate of turn to be used. When the moving hand reaches the calibration corresponding to the angle 2β already determined, the turn should be started as soon as possible. In practice there will be a lag in the actual starting of the turn; for best results the radar operator should call for the turn somewhat before the hand actually reaches the calibration. The correct amount can be learned by experience.

The simple form of range clock procedure described above is effective, except when there is a very large angle (greater than 130 degrees) between the courses of the planes, and an appreciable speed difference. In order to deal adequately with all interceptions at very large angles, two more markers must be added to the range clock, thus producing the standard range clock (Figure 2). Use of this standard clock is fully described in James' report.[6]

[redacted]

PART IV

AIRBORNE FIRE-CONTROL RADAR

Chapter 17

GENERAL CONSIDERATIONS ON AIRBORNE FIRE CONTROL

17.1 INTRODUCTION

This part, consisting of the present chapter and the following five chapters, contains a discussion of various fire-control radar systems developed during World War II, with some suggestions for future developments. The treatment is not complete for all systems, and some have been omitted altogether. Certain systems chosen for their representative nature have been discussed in considerably more detail than others. Although the emphasis is on systems developed at the Radiation Laboratory, others are included to give balance to the picture, especially where the first system of a given type was developed at the Radiation Laboratory, while the responsibility for modifications and refinements (sometimes quite extensive in nature) was turned over to manufacturers working under Service contracts.

17.2 OTHER NDRC FIRE-CONTROL AGENCIES

The Applied Mathematics Panel, under the direction of Dr. Warren Weaver, and Division 7 of NDRC, headed by Professor H. L. Hazen, were concerned with general fire-control developments during World War II. Reference should be made to Vol. 2, Part A of the Summary Technical Report of the Applied Mathematics Panel, written by Dr. E. W. Paxson,[88] and to similar reports for NDRC Section 7.2 (Airborne Fire Control) by Drs. J. B. Russell and G. A. Philbrick.[12, 13] Section 7.2 further allowed its contractors to submit final reports consisting of their interim reports bound together with suitable introductions. One of the Applied Mathematics Panel agencies most active in the field of airborne fire control was the Applied Mathematics Group at Columbia University under the direction of Professor S. MacLane. A survey of this work has been published,[90] as well as a bibliography with abstracts of some of the papers.[117]

17.3 CLASSES OF RADAR SYSTEMS

Fire-control radar systems fall into three general categories. These are discussed in Chapters 18, 19, and 20. Chapter 18 deals with automatic following equipment, that is, radar systems which first locate and then automatically track and range on a target aircraft. Sets of this kind are the most complicated fire-control radar systems; they are so complicated that none were in service by the end of World War II, except for experimental installations in a squadron of night fighters which reached the theater too late to see combat. (The radar sets themselves were coming off the production line in the spring of 1944, but installation was held up pending decisions on related computers and tactical needs.)

Chapter 19 discusses an intermediate kind of equipment which provides for automatic ranging and gives the gunner a scope indication of target position which he can use for tracking. This equipment was simpler than the automatic following equipment and problems of development and installation (including computer tie-in) were solved in time for its use in considerable quantities during World War II.

Chapter 20 treats fire-control radar systems which supply only range-to-target information. Some systems are designed for air-to-air ranging, some for air-to-ground ranging, and others for both. Some of these systems are automatic in operation, others require a radar operator, and all require optical aiming. The historical aspects of airborne range-only radar are discussed in a memorandum[53] by A. F. Sise, chief of the airborne fire-control section of the Radiation Laboratory.

17.4 PROBLEMS IN THE DEVELOPMENT OF AIRBORNE FIRE-CONTROL RADAR

The role of radar is to supply information about the target. To be of any use this information must somehow contribute to gun pointing. During aerial combat a gunner does not have time to read the radar information from dials and scopes, consult firing tables to determine correct aiming point, then point his guns and finally fire. The total duration of a nose attack against a fast bomber is frequently less than two seconds and even a tail attack is unlikely to last more than 20 seconds. Even on the slower attack the correct aiming point changes rapidly with time, so use of tables during flight is impractical. Thus, there must be some kind of computer to transform the radar-supplied information about the target into gun pointing. Some of the problems encountered in integrating radar into a fire-control system are discussed in Chapter 21.

A difficult phase of the development of airborne equipment is assessment. This is important both in the engineering stages and later in Service acceptance tests. A considerable amount of effort went into developing suitable techniques. Assessment problems are discussed in Chapter 22.

After a radar set has been designed and accepted by the Services its proper functioning and use must be assured. Training problems both for maintenance and operation are of primary importance. See Chapter 13 for a discussion of this topic.

17.5 REASONS FOR SLOW PROGRESS OF AIRBORNE FIRE-CONTROL RADAR SYSTEMS

In spite of the very considerable amount of work done in developing airborne fire-control radar systems, very few of them saw combat use. A discussion of reasons for this may be useful in planning future developments, and in preventing a repetition of the mistakes of World War II. Although the points listed below are not all independent of each other, it is the authors' belief that they are sufficiently different to warrant separate listing.

17.5.1 Lack of Overall System Responsibility

This was in the authors' opinion the main cause of delay. Coordination between sight designers and radar designers left much to be desired. This lack of coordination was not helped by the NDRC assignment of sight development to one Division and radar development to another Division. A typical attitude of a sight designer was that his sight would be ready long before any corresponding radar, so he was not greatly concerned with making provision for possible radar inputs. On the other hand the radar systems were frequently designed without much thought about related sights. This point is treated in more detail in Chapter 21, in particular in Sections 21.3.3 and 21.3.4.

17.5.2 Delays Caused by Acceptance Tests

So many new gadgets were thrust upon the testing authorities of the Army and the Navy that any particular item was subject to numerous delays, unless it had some special push from higher up. Many radar sets by-passed the test agencies, but this was not true in the airborne fire-control field. Further discussion of this point is given in Chapter 22.

17.5.3 Delays Due to Training Problems

Complicated equipment such as a radar system requires expert maintenance and a well-trained operator. This is true even at the test level. But here a vicious circle was encountered. Under Army policy a training device for a piece of equipment could not have high enough priority to permit its manufacture until the latter had been approved by the test agency. The situation for maintenance training was similar. Thus, after test approval was given, the system still had to wait for the training of maintenance men and operators. This point is discussed further in Chapter 22 with respect to its influence on the test program.

17.5.4 Delays Due to Slowness of General Airborne Fire-Control Program

This is related to the first reason listed above. A widespread attitude in the Services was that the aiming of guns was one place in which civilian scientific help was not needed. Although the staff of the Secretary of War included several "expert consultants" on radar and other recognized technical developments, it was not until the late spring of 1945 that an expert consultant in the airborne fire-control field was added. Further discussion of this point will be found in various parts of Chapter 21.

17.5.5 Delays Due to Overambitious Programs

The first development of radar for airborne fire control was in automatic following equipment. When it became evident how much time completing such a program would take, the more ambitious projects were tabled and work was begun on simple lightweight systems. This trend is illustrated by the early emphasis on system AN/APG-1, an automatic gun-laying radar set weighing about 700 lb and the much later initiation and development of AN/APG-13, a set weighing less than 100 lb, designed to provide range information for isolated water targets, and which incidentally was one of the few airborne fire-control radar sets successfully used in combat. This point was important as a reason for delay but is probably not of great importance for future developments, especially during peacetime conditions.

17.5.6 Delays Due to Changing Tactical Conditions

By the time lightweight practical radar sets were available for airborne fire control the tactical situation had so changed that they were no longer so urgently needed as earlier in the war. In the last few months of the war losses from enemy fighter action dropped to such an extent that combat commands were no longer pleading for defensive equipment. This resulted in lack of pressure throughout the whole testing and training programs. If combat losses had remained high there would undoubtedly have been considerable use of some of the airborne fire-control radar systems. Even in the case of Falcon (AN/APG-13), which did see successful combat use against river boats in China, further advances of the Japanese almost neutralized the equipment by pushing AAF bases out of practical combat range from suitable targets. The later more complicated systems AN/APG-13B and AN/APG-21 would have been useful here but were not developed soon enough.

17.5.7 Delays Due to Limited Uses of Airborne Fire-Control Radar Systems

Airborne fire-control radar systems do not have the variety of uses encountered in many other airborne systems; consequently the fire-control program did not have as strong support as other airborne radar programs. If the fire-control systems had weighed only a few pounds the lack of other uses would not have been so important, but it was quite understandable that the Services hesitated to install an unproved system which weighed as much as a man or as a small bomb, even though the new equipment, if successful, might save several times its own weight by reducing the amount of ammunition needed. Although there may be a few peacetime applications for fire-control radar sets (such as anticollision or point-to-point communication), it does not seem that these will be sufficient to stimulate commercial developments. This places a strong obligation on the Services to push radar developments in the airborne fire-control field by their contractors and by their research laboratories.

Chapter 18

AUTOMATIC FOLLOWING EQUIPMENT

18.1 OPERATION

18.1.1 Function of Equipment

In an *airborne gunlaying* [AGL] radar system, the scanner or antenna tracks the target airplane continuously and automatically in azimuth, elevation, and range. It searches for a target through a fairly large volume in space, gives the operator angular position and range information on all targets in that volume, and operates with special equipment to identify those targets as friend or foe without optical contact. It can be quickly and simply locked on the desired target in angle and in range, and will thereafter automatically follow the target in those coordinates. The necessary fire-control data are fed from the radar to a computing mechanism which may be either a lead-computing sight or a central-station type of computer. The computing mechanism controls the aiming of turret guns.

In addition to the functions mentioned above, a specific navigational aid, beacon interrogation, is incorporated in night-fighter equipment. AGL can be used offensively in night fighters against attacking bombers or for intruder work. It is used defensively in bombers for tail protection.

In the present chapter, only those systems designed in the United States are discussed. There are some important British developments as well, of which some features are mentioned.

There are at present two fundamental design types of systems, illustrated in Figures 1A and 1B. In one, the antenna is mounted directly on the turret (e.g., AN/APG-16, AN/APG-19); in the other it is separately mounted (e.g., AN/APG-1, AN/APG-2, AN/APG-3). Both must fulfill similar search requirements, but the former need only track through an angle equal to the maximum lead angle whereas the latter must be capable of tracking through a solid angle even greater than that needed for search alone.

18.1.2 Radar Boresight

A conical-scanning antenna, used by all present microwave gunlaying systems, or its equivalent, a lobe-switching antenna, is the heart of the system around which all other components are designed. The antenna has a so-called radar boresight line or radar boresight direction which is defined almost as closely as an optical sight line. This radar boresight direction is obtained by rotating the main lobe of radiated power about an axis which is offset several degrees from the axis of symmetry of the lobe.

A target lying on the radar boresight direction will return the same power from each successive pulse except

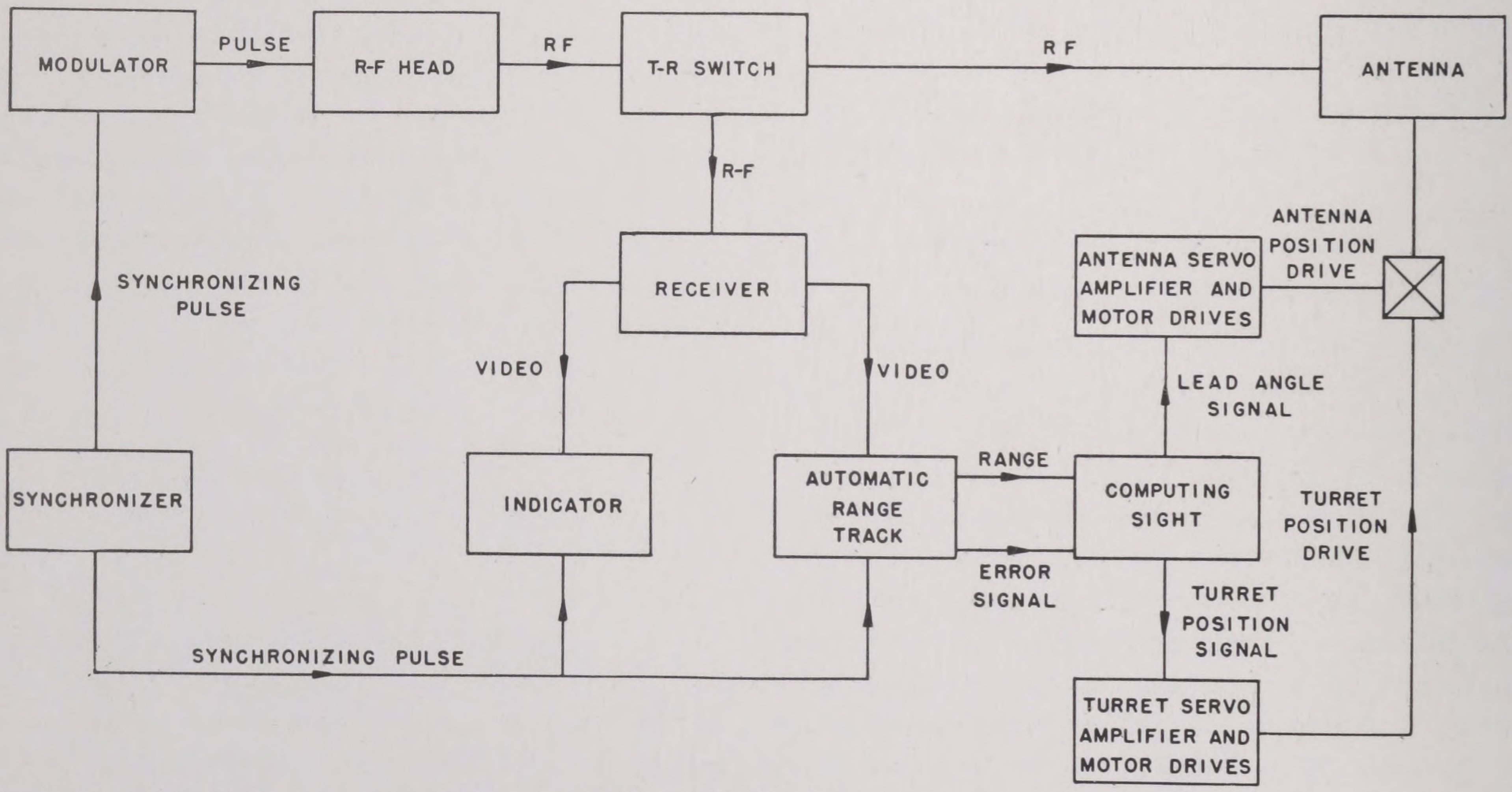

MODULATOR
PULSE
R-F HEAD
RF
T-R SWITCH
RF
ANTENNA
R-F
ANTENNA POSITION DRIVE
ANTENNA SERVO AMPLIFIER AND MOTOR DRIVES
SYNCHRONIZING PULSE
RECEIVER
VIDEO
VIDEO
LEAD ANGLE SIGNAL
SYNCHRONIZER
INDICATOR
AUTOMATIC RANGE TRACK
RANGE
COMPUTING SIGHT
TURRET POSITION DRIVE
ERROR SIGNAL
TURRET POSITION SIGNAL
SYNCHRONIZING PULSE
TURRET SERVO AMPLIFIER AND MOTOR DRIVES

FIGURE 1A. Block diagram of an AGL radar system with the antenna mounted on a turret and operating with a computing sight in the turret.

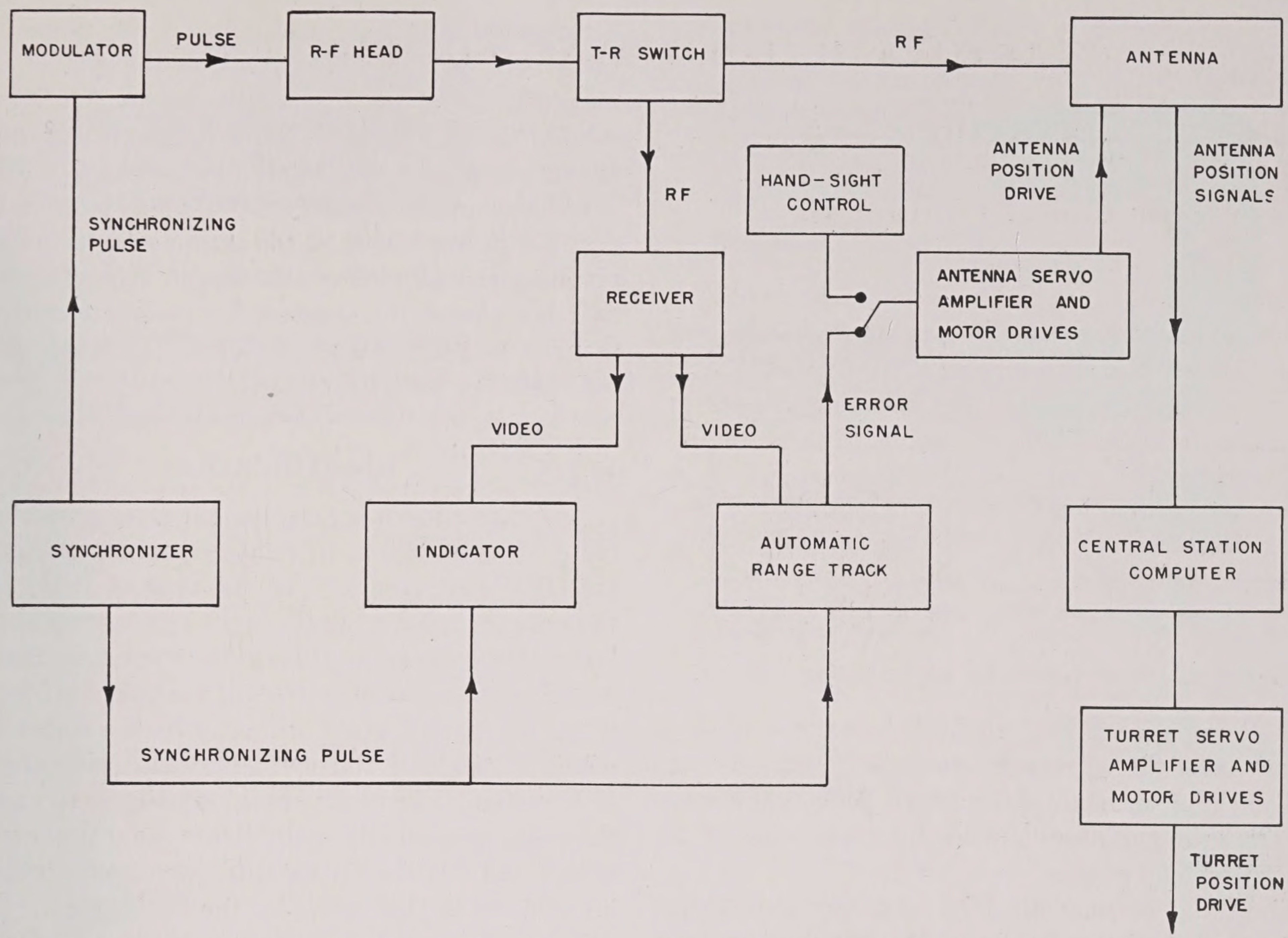

MODULATOR
PULSE
R-F HEAD
T-R SWITCH
RF
ANTENNA
RF
HAND-SIGHT CONTROL
ANTENNA POSITION DRIVE
ANTENNA POSITION SIGNALS
SYNCHRONIZING PULSE
RECEIVER
ANTENNA SERVO AMPLIFIER AND MOTOR DRIVES
ERROR SIGNAL
VIDEO
VIDEO
SYNCHRONIZER
INDICATOR
AUTOMATIC RANGE TRACK
CENTRAL STATION COMPUTER
SYNCHRONIZING PULSE
TURRET SERVO AMPLIFIER AND MOTOR DRIVES
TURRET POSITION DRIVE

FIGURE 1B. Block diagram of an AGL radar system operating with a director type of computer not located in the turret. (There should be a line from the automatic range track box to the central station computer, indicating range input.)

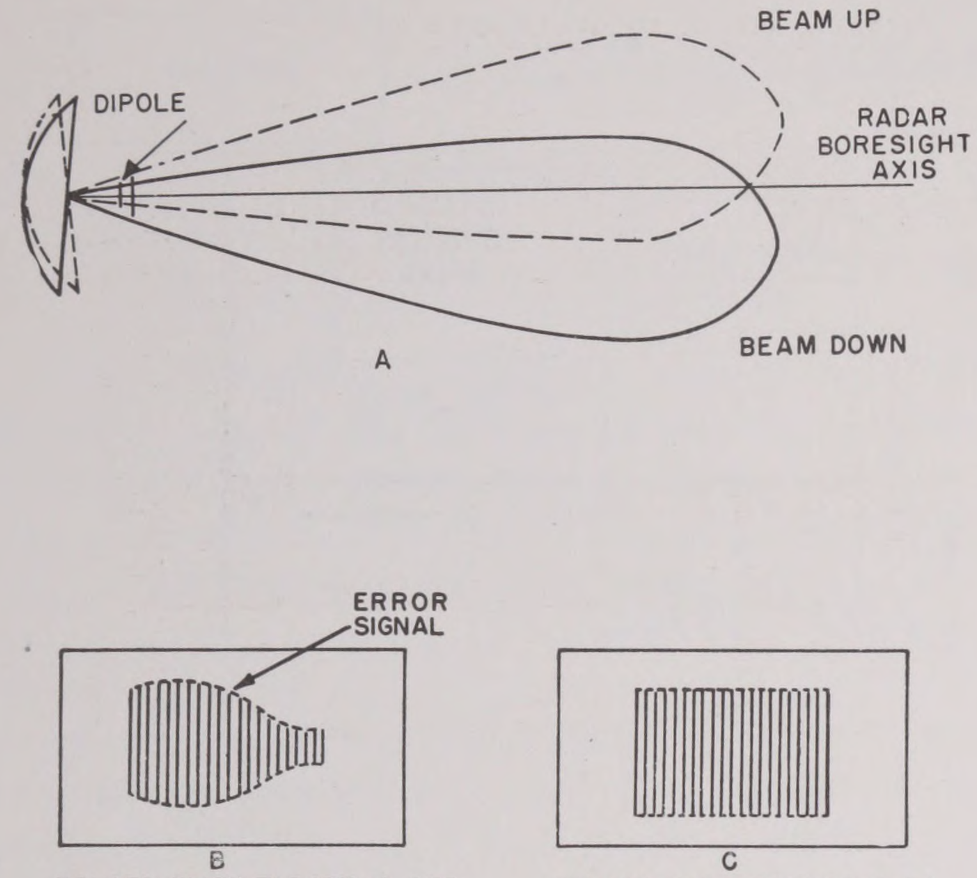
for fluctuations caused by fading and propeller modulation, and by target polarization effects if the spinner includes a rotating dipole. A target lying off the boresight axis, as illustrated in Figure 2B, will return power modulated at the conical-scan frequency and its harmonics, the latter in amounts depending upon antenna design.[22] The phase and amplitude of the fundamental frequency are determined by the angular position of the target in relation to the radar boresight line of the antenna.

18.1.3 Automatic Following

When the system is on track (follow), the signal from the desired target is automatically tracked in range. The output of the tracking gates, which contain video information relative only to the desired target, is fed into a third detector. The output of the third detector is the error signal, that is, the audio envelope of the power received from the desired target. This error signal, when amplified, is fed into a commutator circuit wherein it is compared with conical-scan reference voltages obtained from a generator attached to the antenna. The commutator circuit provides d-c voltages, the polarity and magnitude of which depend upon the direction and amount, respectively, of the error in the azimuth and elevation channels. These d-c voltages are then applied to amplidynes or similar devices which drive the scanner or turret in such a manner as to reduce the error signal to zero.

18.1.4 Computation

Selsyns or potentiometers transmit azimuth and elevation information to the computer or to the computing sight as the case may be, and rate gyros on the scanner, on the turret, or in the sight transmit angular rates. The range unit delivers a d-c voltage to the computer. These data plus ballistic input data determine the lead angle. When the scanner is mounted separately from the turret, selsyn linkage between turret and computer provides the signal to the turret servo-amplifier which causes the turret guns to track



ECHOES WHEN TARGET IS OFF THE RADAR BORESIGHT AXIS

ECHOES WHEN TARGET IS ON THE RADAR BORESIGHT AXIS

FIGURE 2. Conical scanning with rotating reflector.

with the necessary lead angle. When the scanner is mounted on the turret, the computing sight delivers a signal to a servo-amplifier which deflects the scanner from the gun boresight line by the amount of the computed lead angle.

The radar scanner must be harmonized with the guns so that the radar boresight line and the gun boresight line are parallel when no lead is given by the computer.

18.1.5 Search

There are several methods of performing the search function. The simplest and most common is a type of *Palmer scan* illustrated in Figure 3A. An illustration of the search coverage of a type of system used in offense is given in Figure 3B. The antenna persists in a conical scan, but in addition the antenna mount is rotated alternately in azimuth and in elevation, performing a closed loop. The motion may include one or more steps in elevation per cycle. This motion is generally accomplished by means of cams and microswitches which direct power to the azimuth and elevation drives in the proper sequence and duration.

18.1.6 Track

When switching from search to track, the operator must close an action switch which gives him control of the scanner position. Then, while positioning the scanner for maximum return from the target (searchlighting) as indicated on his scope, the operator throws a search-track switch to track, and either puts a range-tracking gate manually on the target echo (as in AN/APG-1, AN/APG-2) or the system automatically locks on the target (as in AN/APG-3, AN/APG-16, AN/APG-19). With the latter the operator can press a range-gate in-out switch, until the gate locks on the desired echo, if there is more than one. Following release of the action switch, the scanner automatically follows the target. When the action switch is closed, the operator has complete control of scanner pointing regardless of the position of the search-follow switch.

18.1.7 Identification

Automatic following equipment is designed to operate with equipment to identify a target as friend or foe (IFF equipment).[57a] In one type of IFF system the radar supplies a trigger to the IFF system and the latter transmits an r-f pulse at the same time that the radar r-f pulse is transmitted. If the target is friendly, it has equipment which will send back a coded reply which is received and converted into video by the IFF system. The radar operator wishing to identify the radar echo merely searchlights the scanner on the target and switches from the video presentation of his own set to that fed it by the IFF system.

18.2 REQUIREMENTS

The requirements placed upon the radar depend in some measure upon the tactical use to which the radar is to be put. These uses may be offensive as in a night-fighter radar, or defensive as in a bomber defense radar.

18.2.1 Requirements Common to Defensive and Offensive Radars

1. The set must be light and compact.
2. It must meet certain specifications on altitude, temperature, and radio noise.
3. The set must directly (or indirectly through associated equipment controlled by it) provide the computing device with target azimuth and elevation, azimuth and elevation rates, and range.
4. The set must be able to track the target airplane in azimuth, elevation, and range with a high degree of accuracy under conditions of maneuvering and of low-level attack, through a large volume in space. The accuracies required depend upon computer requirements, target characteristics, and the characteristics of the firing device. The specifications

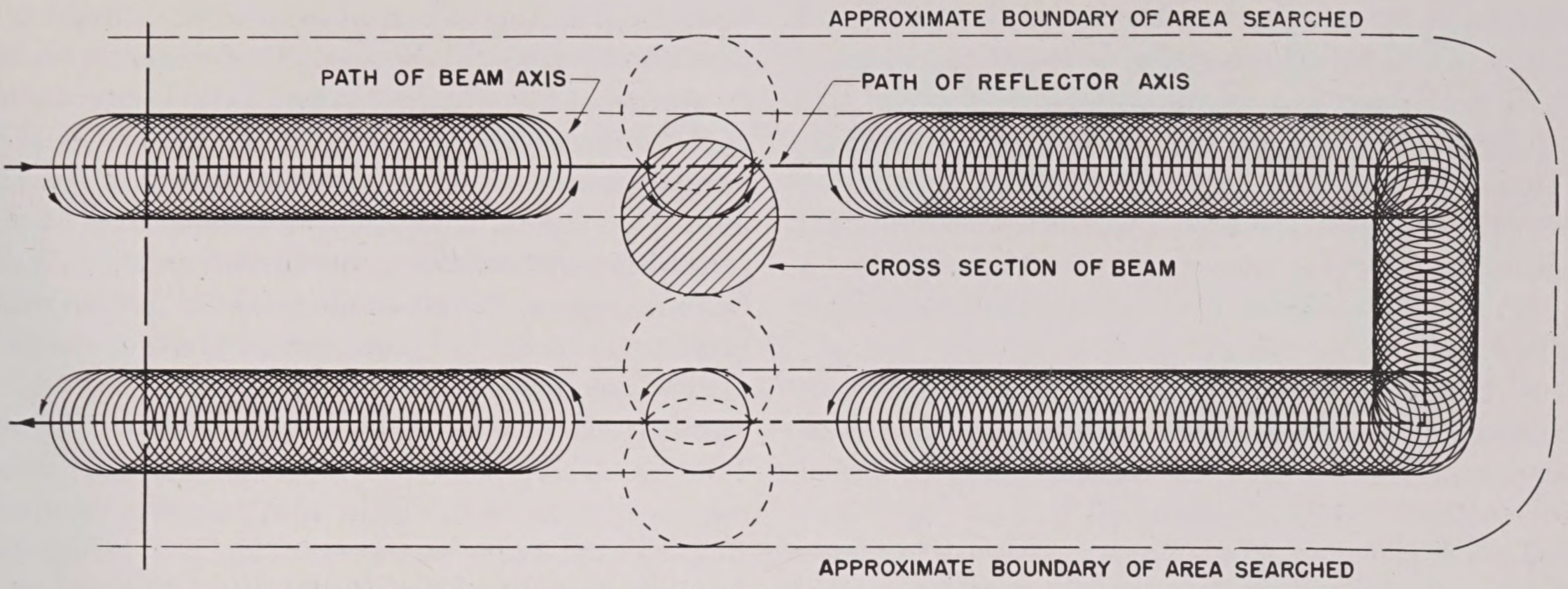

APPROXIMATE BOUNDARY OF AREA SEARCHED
PATH OF BEAM AXIS
PATH OF REFLECTOR AXIS
CROSS SECTION OF BEAM
APPROXIMATE BOUNDARY OF AREA SEARCHED

Figure 3A. Palmer-scan method of searching represented on a flattened surface.

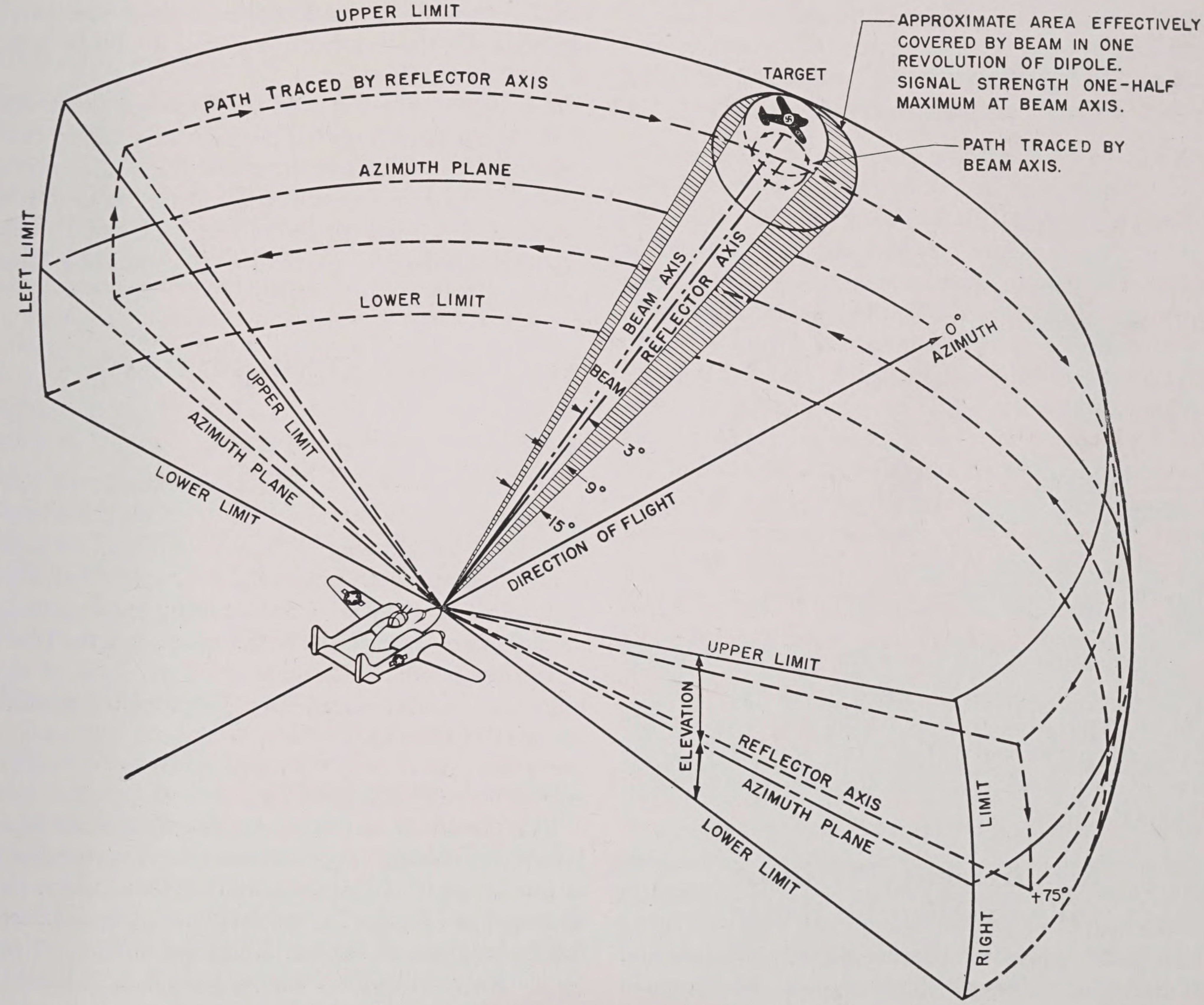

UPPER LIMIT
PATH TRACED BY REFLECTOR AXIS
TARGET
APPROXIMATE AREA EFFECTIVELY COVERED BY BEAM IN ONE REVOLUTION OF DIPOLE. SIGNAL STRENGTH ONE-HALF MAXIMUM AT BEAM AXIS.
PATH TRACED BY BEAM AXIS.
AZIMUTH PLANE
LEFT LIMIT
LOWER LIMIT
BEAM AXIS
REFLECTOR AXIS
BEAM
0° AZIMUTH
3°
9°
15°
UPPER LIMIT
AZIMUTH PLANE
LOWER LIMIT
DIRECTION OF FLIGHT
UPPER LIMIT
ELEVATION
REFLECTOR AXIS
AZIMUTH PLANE
LOWER LIMIT
RIGHT LIMIT
+75°

Figure 3B. Search coverage with Palmer scan.

stipulated by the Services for sets AN/APG-3 and AN/APG-16 called for probable errors of not more than ±¼ degree in azimuth and in elevation, and not more than ±25 yd in range, when the tracking rate is less than 22.5 degrees per second, and the acceleration is less than 20 degrees per second per second.

5. The desirable minimum tracking range is 75 to 100 yd.

6. Search periods must be short because of the increased flexibility of attack approaches. If a single scanner performs both search and track functions, the switchover must be rapid.

7. The set must provide means of positive identification of the target plane as friend or foe so that optical contact with the target is not necessary.

8. The Services have stipulated that in daytime operations where tracking is done optically, the equipment should supply only range.

18.2.2 Requirements Pertinent Only to Offensive Radar

Night fighters must be able to contact enemy intruder planes with or without the aid of *ground controlled interception* [GCI]. They should further be able to detect enemy bombers out to 20,000 yd or better. The system must have large search and track coverages. (Coverage of AN/APG-1 and AN/APG-2: search ±82.5 degrees in azimuth, and from −12.5 to +17.5 degrees in elevation; track ±82.5 degrees in azimuth, and from −12.5 to +80 degrees in elevation.) A large tracking coverage is desirable to permit flexibility in approach and efficient utilization of fire coverage. The desirable search period is a debatable point depending largely upon the angular limits of the volume covered. A period of 2 or 3 sec should be short enough to satisfy all present tactical requirements.

An indication of target position, range, and closing speed must be given the pilot to facilitate contact and to permit him to home on the target and to fire his fixed guns as well as the turret guns, if he so desires. It also enables him to follow a maneuvering or "jinking" target.

18.2.3 Requirements Pertinent Only to Defensive Radar

An ideally protected bomber should have fore and aft gunlaying radars which give spherical coverage in search. Track coverage should be somewhat better than the turret coverage to permit full utilization of the turret fire power. Nose coverage range should be greater than tail coverage range. With a closing rate of 800 mph, a detection range of 20,000 yd would be needed in order to give 50 sec warning. At the end of World War II, 5,000 yd was considered adequate for tail protection. The use of guided missiles, faster fighters, rockets for air-to-air combat equipped with proximity fuses, or new tactics may necessitate greater coverage.

When search ranges become greater than the altitude at which the aircraft is flying, it will be necessary to provide adjustable limits on the automatic range-search gate or the equivalent to prevent it from locking on the altitude signal; some special means of preventing ground echoes from obscuring air targets should also be provided (see "Indication," Section 18.6.1). In doing this, it is necessary to remember that the operator is primarily a gunner, and consequently the number of controls should be kept as small as possible.

It is highly desirable to be able to search and track at the same time. This requirement may necessitate separate systems for search and for track. A compromise such as a system which could be momentarily switched from track to search and back again without interrupting the continuity of computing data might suffice.[19]

18.3 DESIGN CONSIDERATIONS

18.3.1 Wavelength

Choice of wavelength is dictated primarily by considerations of power requirements, absorption, susceptibility to jamming, and antenna requirements. Other factors, as yet not completely evaluated, also may affect the choice of wavelength. These include the influence of refraction by jet gases, and the effect of the reduction of the cross-sectional area of the target, as in ultra-streamlined jet-propelled aircraft and guided missiles.

Antenna Considerations

The design of antennas for fire-control systems presents problems very similar to those encountered in the design of bombing and AI systems, which are discussed in Chapter 7 (especially in "Factors Affecting Radar Range," Section 7.2.2) and in Chapter 15, respectively. Thus, in changing from S to X band it was found possible to make a considerable reduction in weight and in size. AN/APG-1 and AN/APG-2, S band sets, weighed approximately 600 lb exclusive of the weight of the mounting brackets, whereas AN/APG-3 and AN/APG-16, X band sets, weighed approximately 225 lb installed. (These figures do not include the weight of the a-c power supply.) This reduction resulted from increased knowledge of the art, better packaging, the use of smaller r-f components, and decreased antenna size. A further reduction, though not so great, would be expected at K band. It might well be possible to design two K band antennas, one a continuously searching antenna, the other a tracking antenna, perhaps with an r-f switch between the two, so that only one modulator and r-f head would be required. Together these might approximate the size and weight of a single X band antenna, and at the same time meet the search-track requirements laid out in Section 18.2. Antenna development is discussed further in Section 18.6.1.

OTHER CONSIDERATIONS

Preliminary investigations indicate that the index of refraction of hot jet gases is very small. If, however, an AGL antenna is located very near a jet exhaust and the radar boresight axis is in the region of grazing incidence with the direction of flow of the jet gases, harmful refraction of the radar beam can take place, causing the antenna to be mispointed.

Proper streamlining has been found to reduce the effective cross-sectional area of a target to microwaves. Hence, an ultra-streamlined jet-propelled fighter airplane may be extremely difficult to detect with microwave radar. (The absence of propellers also has an effect.) The effect of streamlining in reducing the effective target cross-sectional area is greater at these very short wavelengths than at longer ones.

18.3.2 Antenna

THE SCAN FUNCTION

A conical scan or its equivalent is required to determine the angular position of the target. There are two principal methods of obtaining this conical scan. A parabolic reflector may be mechanically offset from the feed axis by approximately half the desired beam offset angle and the reflector may be rotated around the feed axis as shown schematically in Figure 2. AGL systems using this type of antenna are AN/-APG-3, AN/APG-16, and AN/APG-19. Such an antenna is feasible for systems operating at X or K bands, but with S band the large size required for the reflector causes mechanical difficulties. Early development models at S band used a rotating feed which was mechanically offset from the paraboloid rotation axis.

The second method, in which the feed and the axis of the parabolic reflector are coincident, is electromechanical. The main lobe of radiated power is offset from this principal axis electrically by use of a choke located behind the dipole. The distance between the choke and the disk reflector at the end of the feed is chosen to cause resonance at the radio frequency used. The phase of the energy radiated by the outside of the feed between the choke and the disk reflector combines with that radiated by the dipole after reflection by the paraboloid in such a manner as to cause a shift in phase of the wave front, offsetting the beam from the axis of the paraboloid (and feed) by the desired amount.[21] Mechanical rotation of the feed produces the conical scan. This method is well suited for S band and is used in the AN/APG-1 and AN/APG-2 systems. It is shown in Figure 4. Rotating the feed presents certain problems in design not found in other types of conical-scan mechanisms. Since S band wave guide is inconveniently large, it is necessary to use coaxial feed, and careful attention must be paid to the design of the coaxial high-speed rotary joint. A poorly designed joint will cause the impedance facing the magnetron to change as the feed rotates, thereby causing the magnetron to change frequency (frequency pulling) at the conical-scan rate. Frequency pulling at the conical-scan rate introduces spurious signals at the error signal frequency and its harmonics,[47] which result in the mispointing of the antenna and in erratic tracking, unless steps are taken to nullify its effect. These spurious signals arise from the unequal action of the rela-

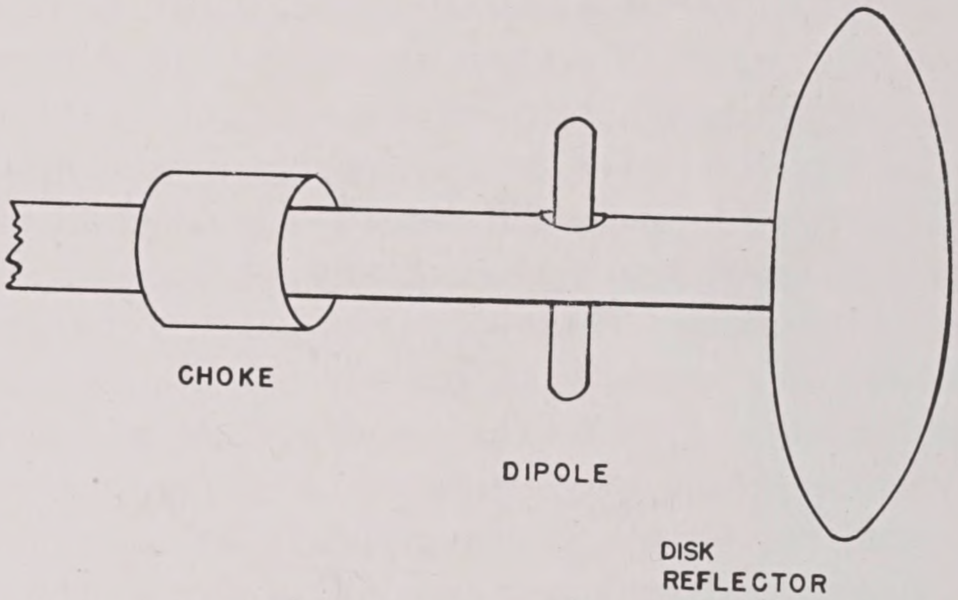


FIGURE 4. Electrical-offset antenna feed, for conical scanning (see also Figure 10).

tively narrow band-pass of the i-f strip upon the different frequencies present. The effects of this frequency pulling can be lessened by a fast-acting *automatic frequency control* [AFC] — an i-f strip several times wider than would be required in the absence of frequency pulling — and by a broad-banded duplexer. (The duplexer is that portion of the r-f feed which interconnects the magnetron, output coaxial line, and *transmit-receive* [TR] box.) A properly designed AFC will reduce the frequency modulation of the i-f signals to a tolerable amount; amplitude modulation of the signal caused by changes in intermediate frequency will be smaller for a broad i-f strip than for a narrow one; and a broad-band duplexer will reduce the amount of frequency pulling of the magnetron caused by changing impedance at the antenna. At least two of these precautions are desirable to provide adequate protection against the harmful effects of faulty operation of the high-speed coaxial rotary joint.

The signal obtained with this type of antenna is not so good as that obtained with the rotating offset paraboloid. The r-f polarization rotates with the feed, and any degree of polarization of the target introduces into the signal undesirable components at harmonics of the conical-scan frequency. It also introduces variable phase shifts in the fundamental frequency (maximum approximately 30 degrees) and in its harmonics. These shifts can increase the time required for synchronization, which is the time required for the system to lock on the target, and, after synchronization, can cause the antenna to spiral around the target. Similar phase shifts occur with rotating paraboloid antennas but to a considerably smaller degree.[22]

Most other scanning methods are untried and only one is discussed in this section.

Electronic switches have been devised which enable the switching of power from one feed to another.[27, 31] An antenna with four feeds (corresponding to beam up, right, down, left) activated by such switches in the proper sequence would give the equivalent of a conical scan.

The Sperry AGL-2 system, operating at X band, obtained the conical scan by rotating the feed and reflector together. Their common axis was offset from the axis of rotation by a small angle. The General Electric pantograph scanner, operating at X band, utilized a mechanically offset rotating feed to obtain the conical scan.

The speed of conical scan affects the operation of the system in several ways. There are frequency components in the error signal which enter from sources beyond the control of the designer. It is desirable, of course, to choose a conical-scan frequency that will fall outside of the bandspread of these undesirable but unavoidable frequencies. These frequencies are caused by propeller modulation,[49] which is an amplitude variation of the return echoes caused by the cyclic change in reflection by the target propeller blades. They also result from fading of the target signal strength. The presence of these signals at the conical-scan frequency and, with certain types of commutator circuit, at its harmonics will cause improper tracking. Since high conical-scan rates are desirable for the sake of servo stability and speed of response, it would be best to choose a conical-scan rate above the bandspread of propeller modulation and fading frequencies. However, this high rate has not been mechanically feasible.

PATTERN

A gunlaying antenna should have low side lobes, narrow beam (10-degree maximum) and crossover power consistent with the requirements of crossover slope and maximum range tracking. Low side lobes are desirable to permit search and track beyond altitude signal range. A narrow beam will permit tracking at low altitudes. The latter consideration is of prime importance in the design of night-fighter radar. It is important that the main lobe be nearly symmetrical in the planes of the electric and magnetic vectors (E and H planes) to prevent the introduction of an excessive variable phase shift in the fundamental of the return signal and the introduction of excessive harmonics.[22]

SEARCH SCAN

The most commonly used search scan is a type of Palmer scan illustrated in Figure 3. Azimuth and elevation coverages are limited by mechanical considerations and by the maximum time interval which can be tolerated for a complete scan. Elevation coverage is further limited by the beamwidth and the offset angle. When the offset is obtained by tilting the reflector off the rotation axis, the elevation coverage for a single azimuth scan is approximately equal to the beamwidth plus four times the offset angle. If, as in AN/APG-3 and AN/APG-19, the antenna is designed to have two offset angles, the smaller one for track and the larger one for search, increased elevation coverage can easily be obtained.

Scanning loss is negligible in this type of search pattern, for azimuth and elevation slewing rates are limited to fairly low values.

It is difficult, however, with this type of scan to obtain large coverage in the short period required. One means of obtaining large coverage and a short period is by use of a rotating reflector and feed assembly nodding from the axis of rotation. The Sperry AGL-2 spiral-scan antenna is of this type. It gives hemispherical coverage with an effective period of 1 sec.

18.3.3 Servomechanism

Only the high lights of the servo design problem will be treated in this chapter. A more complete discussion may be found in reference 56a.

Error-Signal Filtering and Commutation

If the beamwidths in the *E* and *H* planes of the antenna radiation pattern were the same, if they did not change with rotation (except, of course, for shift of center), and if the r-f polarization remained constant, then [22] the frequency components of the return signal from the target would be so phased that the effect of commutation upon each component would be to deliver voltages to the scanner servo-amplifier which would cause the scanner to move in the proper direction. All these conditions are not realized in practice; however, they are approached in a well-designed antenna. Therefore the third detector network, the error-signal filters, and the amplifier should pass the signal undistorted and with small relative phase shift between the fundamental frequency and its harmonics, if these harmonics are to be put to use in driving the scanner. The band-pass of these networks is chosen so as to reduce or eliminate undesired components in the error signal.

Commutation of the error signal can be described briefly as follows. A sine wave error signal can be broken up by commutation (as illustrated in Figure 5) into d-c components corresponding to the angular pointing error in azimuth and elevation. Current automatic airborne gunlaying systems employ full-wave commutation at the conical-scan frequency. Taking the error-signal channel of the servo-amplifier of AN/APG-1 or -2 (illustrated in Figure 6) as an example, the operation is as follows. Four sine wave voltages phased 90 degrees apart are applied to the plates of the commutator tubes in pairs. Each tube is then turned on for ½ cycle of the conical-scan rotation. The error signals from a push-pull amplifier are applied to the grids of each pair of tubes. The differential d-c voltages on the cathodes are a measure of the amount and direction of the error. There is no differential d-c output for even harmonic signal input, but there is a differential output for odd harmonics. When considerable amounts of second harmonic are present in the error signal, as where the system has a rotating feed and hence rotating polarization, this component must be attenuated before the signal is commutated. Otherwise the commutation interval depends upon the size of the second harmonic, and the tubes are not dynamically balanced. If square-wave commutation for intervals of 120 degrees is used, the effect of odd harmonics is made negligible and the third harmonic is eliminated.[22]

Stability and Time Lag

When the scanner is mounted on the turret, special servo stability problems arise. As shown in Figure 7, the radar delivers d-c voltages to drive the turret in which the computing sight is mounted. The sight delivers a signal to a servo-amplifier which sets the scanner off by the amount of the lead angle. The time constant of the sight is variable, increasing with range.[58] Synchronization, that is, switching from search to track, is done at long range, where the time constant of the sight is greatest and where the lead angle is greatest. Overshooting is greatest at long range, because of the large lead angles; this presents a serious problem because of the large time constant of the sight. Unless special means are taken to prevent this condition, the time for synchronization is intolerably long. One such means, utilized in one version of AN/APG-16, is to set the time constant of the sight at a small value and hold it there until synchronization is almost completed. This is accomplished by fixing the range input to the sight at a medium value until the turret is within a degree or so of the position computed for that range. At that time radar range takes over and synchronization continues smoothly and quickly. Further discussion of stability is given in Section 19.1.3.

Search, Pointing, and Tracking Provisions

The Palmer-scan search function may be accomplished by feeding d-c voltages in the proper sequence and duration into the scanner servo-amplifier from sources directly on the scanner controlled by cams and microswitches. Alternatively, a-c scanning voltages may come from a separate motor-driven switch-

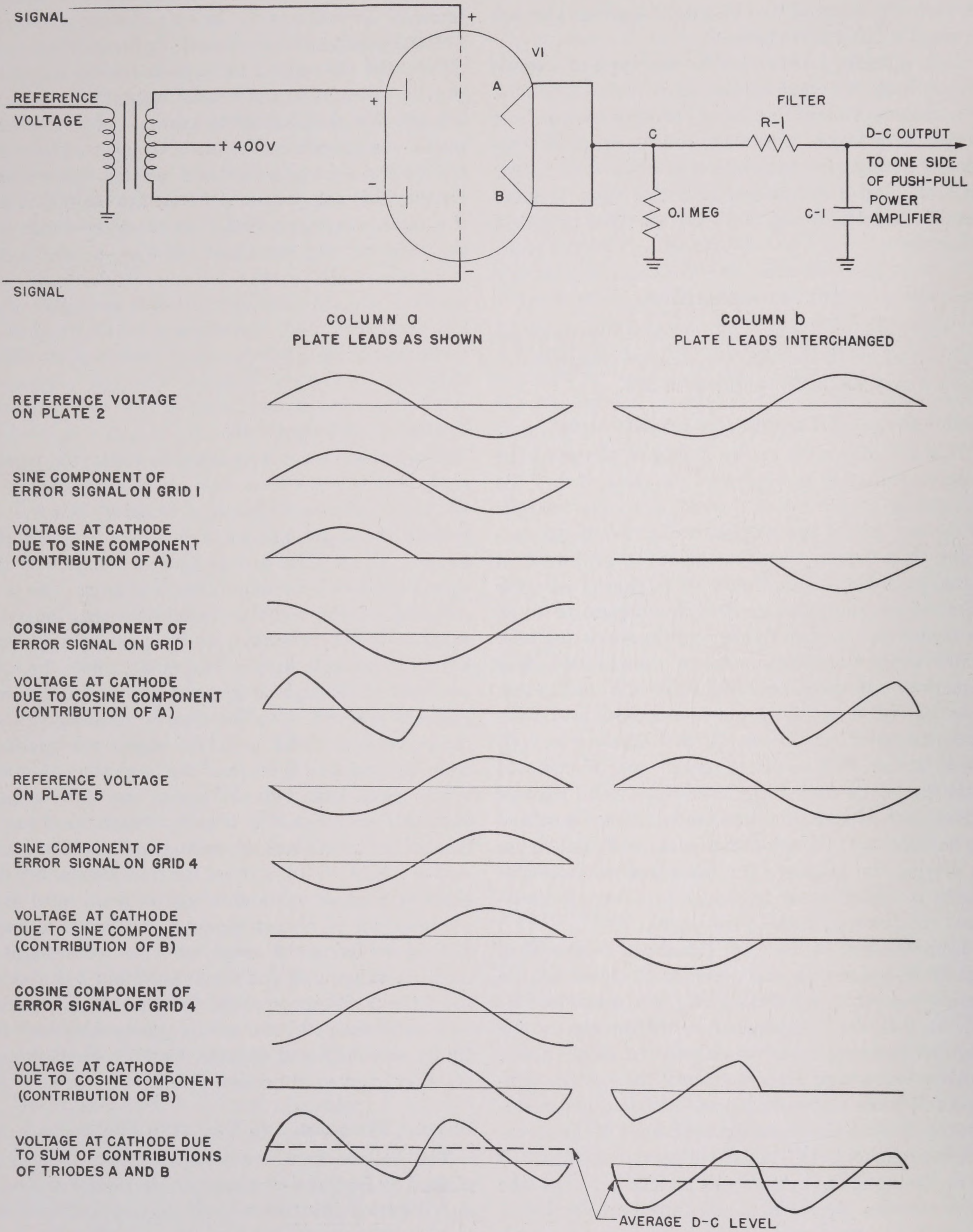

SIGNAL
+
VI
REFERENCE
VOLTAGE
+ 400V
A
B
+
−
FILTER
R-1
C
D-C OUTPUT
TO ONE SIDE
OF PUSH-PULL
POWER
AMPLIFIER
0.1 MEG
C-1
−
SIGNAL
COLUMN a
PLATE LEADS AS SHOWN
COLUMN b
PLATE LEADS INTERCHANGED
REFERENCE VOLTAGE ON PLATE 2
SINE COMPONENT OF ERROR SIGNAL ON GRID 1
VOLTAGE AT CATHODE DUE TO SINE COMPONENT (CONTRIBUTION OF A)
COSINE COMPONENT OF ERROR SIGNAL ON GRID 1
VOLTAGE AT CATHODE DUE TO COSINE COMPONENT (CONTRIBUTION OF A)
REFERENCE VOLTAGE ON PLATE 5
SINE COMPONENT OF ERROR SIGNAL ON GRID 4
VOLTAGE AT CATHODE DUE TO SINE COMPONENT (CONTRIBUTION OF B)
COSINE COMPONENT OF ERROR SIGNAL OF GRID 4
VOLTAGE AT CATHODE DUE TO COSINE COMPONENT (CONTRIBUTION OF B)
VOLTAGE AT CATHODE DUE TO SUM OF CONTRIBUTIONS OF TRIODES A AND B
AVERAGE D-C LEVEL

FIGURE 5. Basic unit of phase detector — functional diagram.

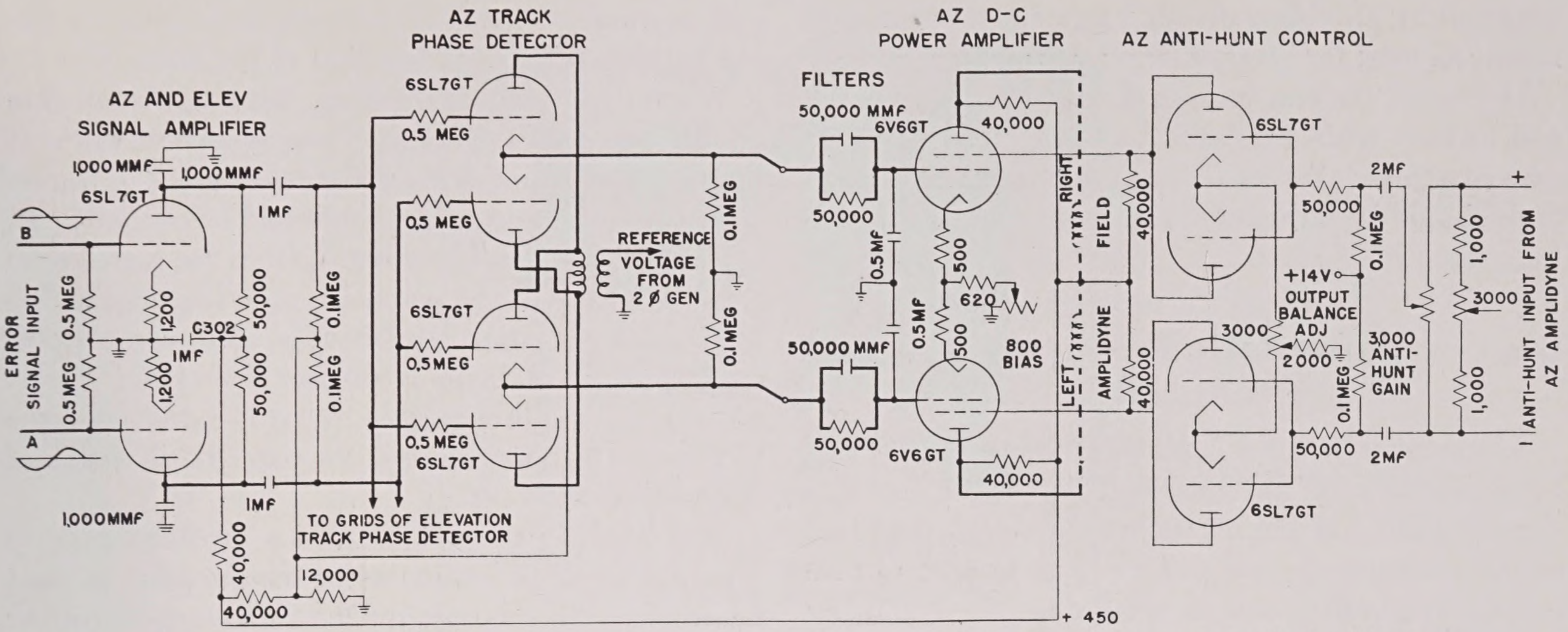

AZ AND ELEV SIGNAL AMPLIFIER
AZ TRACK PHASE DETECTOR
AZ D-C POWER AMPLIFIER
AZ ANTI-HUNT CONTROL
FILTERS
ERROR SIGNAL INPUT
6SL7GT
6V6GT
REFERENCE VOLTAGE FROM 2 ø GEN
TO GRIDS OF ELEVATION TRACK PHASE DETECTOR
RIGHT
LEFT
AMPLIDYNE FIELD
+14V
OUTPUT BALANCE ADJ
ANTI-HUNT GAIN
800 BIAS
ANTI-HUNT INPUT FROM AZ AMPLIDYNE
C302
+ 450
A
B

FIGURE 6. Simplified schematic of AN/APG-1 and -2 servo-amplifier circuits for automatic tracking.

ing source, in which case there are selsyn tie-ins with the scanner, and the selsyn signals are delivered to the scanner servo-amplifier.

If the scanner is mounted on a stationary platform, pointing or searchlighting may be accomplished by feeding the output signals of selsyn or potentiometer linkages between the sight or hand-sight control and the scanner into the scanner servo-amplifier. If the scanner is mounted on the turret, the same may be accomplished, of course, by positioning the turret.

Tracking is accomplished by feeding the radar error signal into the scanner servo-amplifier or, if the scanner is mounted on the turret, by feeding the d-c outputs of the commutator into the turret servo-amplifier.

18.3.4 Automatic Range Tracking

For detailed information on particular range circuits, consult the Radiation Laboratory Technical series, especially reference 54.

Aside from meeting the accuracy requirements set forth in Section 18.2, it is desirable to have the range-circuit design provide for operation against window countermeasures. If a night-fighter AGL range circuit tracks on the trailing edge of the echo, and if the range circuit of the defensive type of equipment tracks on the leading edge of the echo, window is much less likely to pull the range gate off the target. This is because the range motion of the window is in a direction opposite to the direction of the unbalance of the tracking gates. Such unbalance may be

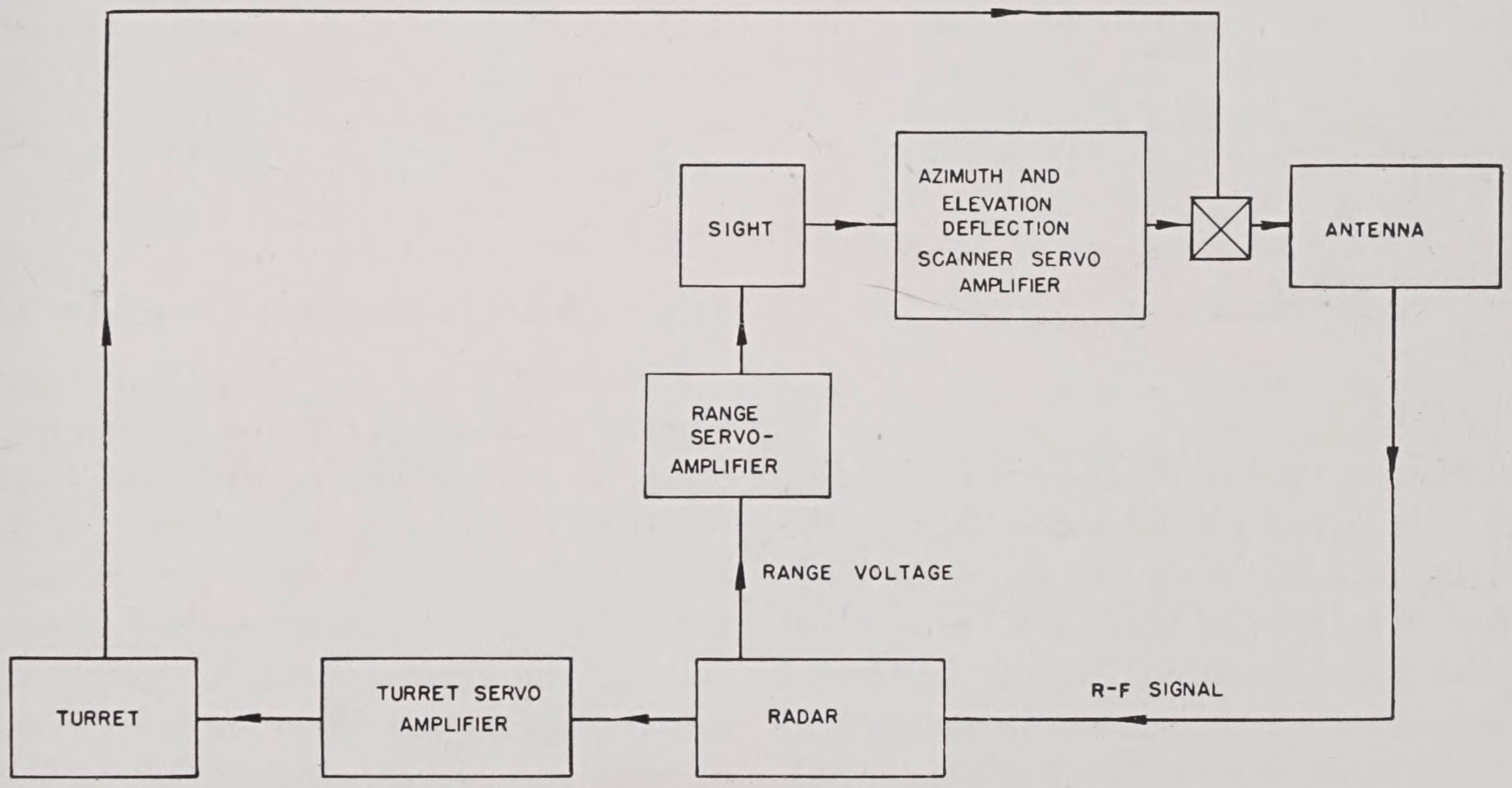

SIGHT
AZIMUTH AND ELEVATION DEFLECTION SCANNER SERVO AMPLIFIER
ANTENNA
RANGE SERVO-AMPLIFIER
RANGE VOLTAGE
R-F SIGNAL
TURRET
TURRET SERVO AMPLIFIER
RADAR

FIGURE 7. Block diagram of typical servo system when antenna is mounted on the turret.

achieved by providing unequal gains in the dual gate networks used for automatic range tracking.

Defensive systems require automatic range search and lock-on with provision for advancing the range gate to adjacent targets. The automatic range search limit should be adjustable to keep it within the altitude signal.

18.3.5 Automatic Frequency Control

Asymmetry in the r-f joints, faulty contacts, and nonuniformity of antenna housing can cause frequency pulling of the magnetron. Frequency pulling at the conical-scan rate and its harmonics can cause mispointing of the antenna, the degree of mispointing depending upon the amount and character of the frequency pulling, the band-pass characteristic of the receiver strip, and the amount of local oscillator detuning. A fast-acting AFC will eliminate most of such trouble. The required AFC characteristics are determined by the nature and amount of pulling involved, the time interval during which the pulling takes place, and by the amount of pulling which could be tolerated without AFC. The amount which can be tolerated can be calculated from knowledge of the antenna pattern, the i-f band-pass characteristic,[47] and the loop gain of the servo.

18.3.6 Automatic Gain Control

Automatic gain control [AGC] is required to maintain the signal level at the receiver output as the strength of the received signal varies because of fading and range changes, and to hold the effective servo-loop gain constant. It must be sharply attenuated at the error-signal frequency to prevent loss of and phase shift in the error signal.

18.3.7 Indicators

Scope Presentation

The B type of presentation (range versus azimuth), to which has been added a small a-c voltage on the horizontal plates (see Figures 8 and 9), is the basic indication used on search and track in all production AGL systems designed to date (1945) in the United States. The a-c voltage is at the same frequency and in phase with the azimuth component of the conical-scan motion and is added to the azimuth potentiometer position voltage. Its purpose is to indicate the instantaneous azimuth position of the main lobe.

When the system is tracking, the range track gate is also shown on the scope in one of several ways. It may be in the form of a video signal similar to the return echo when on target (AN/APG-1, -2, and -3), or as a dot displaced in azimuth from the target echo (AN/APG-16). If the scanner is mounted on the turret, a turret position marker may be shown periodically as well. A type C display (elevation versus azimuth) is made available in night-fighter systems so that the operator can tell the pilot the elevation of the target.

Night-fighter systems require a modified type G presentation on a remote scope for the pilot, so that he can home on a target and follow a maneuvering or jinking target. In addition to the spot and wings indicating the angular position and range of the target, which the type G presentation provides, an artificial horizon is put on the tube. Mechanical or electronic switches are used to alternate these indications on the tube face so that there is no discernible flicker. Engraved lines on the tube face cap indicate firing range.

Spiral-scanning systems require a combination of two or more indicators. One combination, for example, is a B scope and a B′ (elevation versus range) display.

Meters

Night-fighter AGL radars must indicate range and range rate to the pilot. Meters can perform this function and they place little or no burden on the range unit.

In some systems jitter meters have been provided. These indicate the amplitude of the jitter of the scanner around the target. Such a meter is useful if the servo audio gain control is available both to the operator and for servicing purposes.

18.3.8 Antijamming Considerations

A detailed discussion of antijamming provisions is beyond the scope of the present chapter. In general, however, it may be said that antijamming precautions, such as narrow beam, short pulse duration, wavelength flexibility, short time constant following the video detector, instantaneous automatic volume control, unbalanced tracking gates, blanking the initial pulse in the video amplifier rather than the i-f strip, and vertical antenna polarization are all applicable to automatic gunlaying systems.

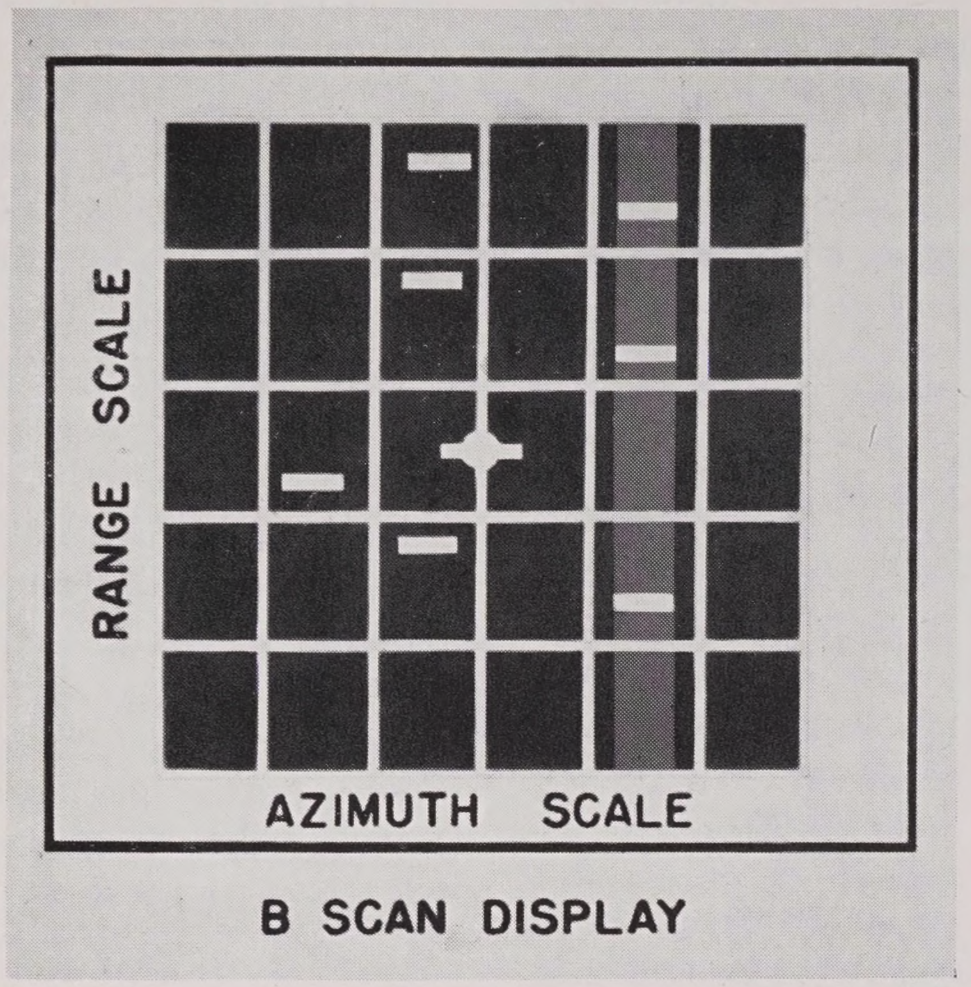

RANGE SCALE
AZIMUTH SCALE
B SCAN DISPLAY

FIGURE 8. Typical presentation of B scope when system is searching.

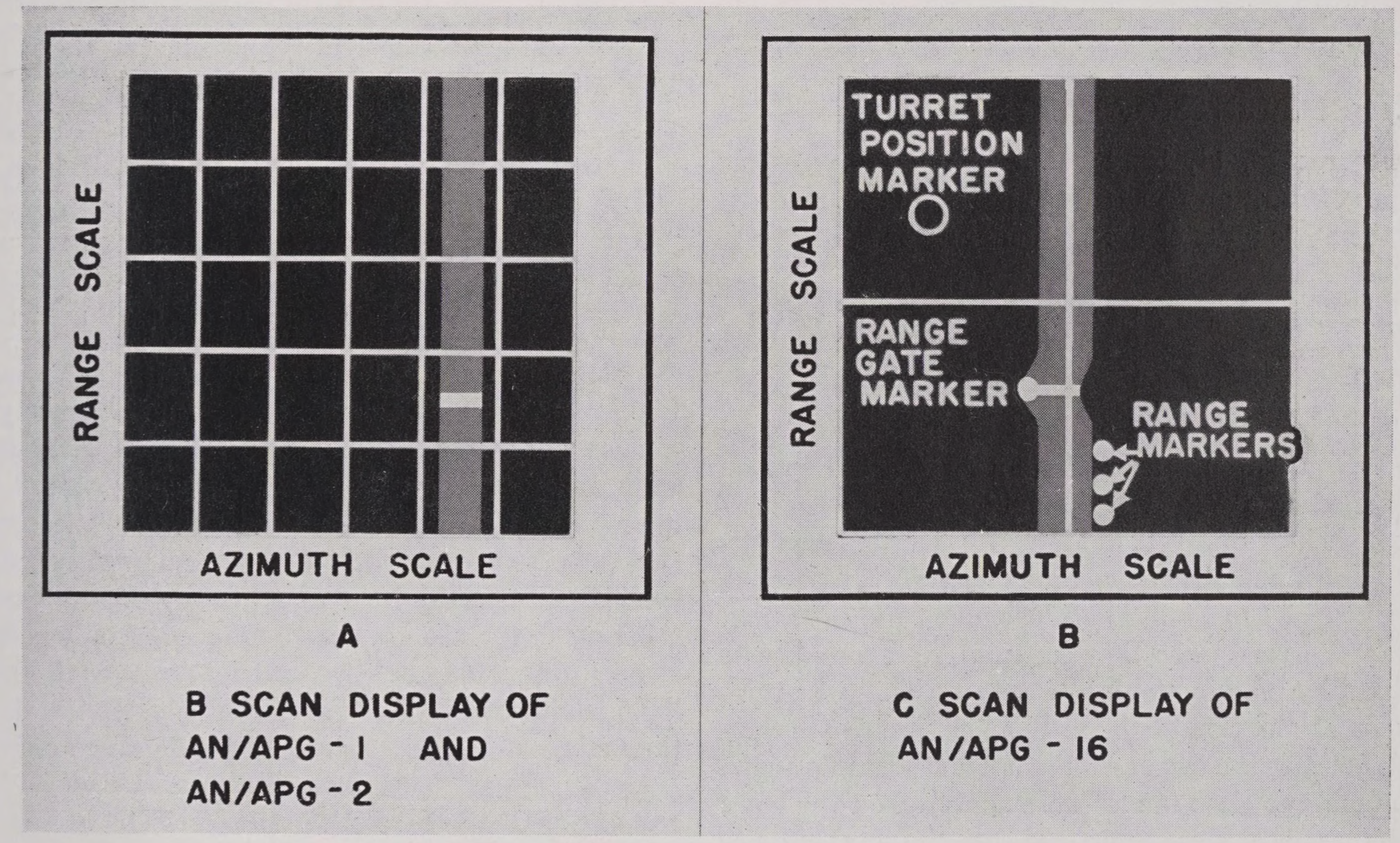

RANGE SCALE
AZIMUTH SCALE
A
B SCAN DISPLAY OF AN/APG - 1 AND AN/APG - 2
TURRET POSITION MARKER
RANGE GATE MARKER
RANGE MARKERS
RANGE SCALE
AZIMUTH SCALE
B
C SCAN DISPLAY OF AN/APG - 16

FIGURE 9. Typical presentation when systems are tracking.

18.3.9 Special Provisions

BORESIGHTING

The scanner radar boresight direction and the gun boresight line must be harmonized, and provisions must be made in the design of the radar to permit the determination of the radar boresight direction, and to facilitate the optical harmonization.[30, 32]

When there is a second harmonic in transmitted power along the radar boresight line because of asymmetry of the beam in the *E* and *H* planes, a simple first echelon procedure for determining the line can be set up.[36a] In general boresighting presents serious problems which are not treated in this book.

IFF

Identification is highly important and usually not easily accomplished. In many cases, IFF equipment requires that the radar supply a synchronizing trigger and accept a video response. Some systems such as Black Maria place special design requirements on the radar. This, and other IFF equipment, is discussed in the Radiation Laboratory Technical Series.[57b]

Warning Buzzer and Light

Defensive AGL equipment is used on long tedious flights in which the gunner is likely to lose his alertness. For this reason it is desirable to have the radar automatically give visual and aural notice in the form of a light and a buzzer or similar device operated by the range circuit when a target is detected in the search area.

18.4 ELEMENTS OF PARTICULAR SYSTEMS

Figures 10, 11, 12, 13, and 14 illustrate various types of AGL antenna assemblies and designs. Most of them are units of production systems.

18.5 ACCURACY

18.5.1 Photo Scoring

Tracking tests were made at East Boston Airport and Boca Raton, Florida, on an AN/APG-1 system installed in a YP-61 night fighter, using small aircraft such as an AT-11 or an O-47 as targets. Analysis of these films showed a probable error in antenna tracking of 2 to 4 mils in both azimuth and elevation. Greater errors, when they occurred, were found to be caused by malfunctioning of some part of the equipment. Evaluation of the films at close range is difficult because the target subtends a considerable angle. The films at close ranges were analyzed on the basis of hits in vital areas compared with the total number of rounds. Data were taken from every fifth frame of films made with an exposure film speed of 16 frames per sec.

Film records indicate that there may be some special computer or possibly radar servo problems arising in connection with night-fighter AGL. The usual night-fighter target is a medium or heavy bomber, and it is found that the radar beam will wander over the target airplane when tracking, although favoring the engines somewhat. This wandering occurs at rates which can be interpreted by the computer as target motion and may, therefore, result in false gun aim. Further study of this problem is needed.

18.5.2 Firing Tests

Tests of AN/APG-1 installed in a YP-61 equipped with a modified General Electric 2CH1L2 Central Station computer were conducted at Brownsville, Texas. A rectangular plastic flag, 6 × 30 ft, with a centered corner reflector was found to be the best target.[137]

Some of the results (using this type of target) are given in Tables 1 and 2. They compare very well with the scores of a good gunner firing under ideal conditions without radar aid. However, AGL cannot yet replace the gunner. It is a complex piece of equipment and, at least at this stage of the art, cannot be expected to be operational 100 per cent of the time. It is to be hoped that, in the future, completely automatic operation can be used at all times, and provisions made for the gunner to take over only if the system fails. This would be an advance over the policy prevailing in World War II, namely, that in daytime missions the radar should provide range only.

Table 1. Sitting duck missions.

Range	Target position	Rounds	Hits	Score
300 yd	45° az., 20° el.	400	160	40%
900 yd	45° az., 20° el.	400	22	5.5%
900 yd	45° az., 20° el.	400	14	3.5%

Table 2. Passing attack missions.

Range	Target position	Rounds	Hits	Score
400–300 yd	35° to 75° az., 20° el.	400	160	40%
400–300 yd	35° to 75° az., 20° el.	400	136	34%
650–500 yd	35° to 75° az., 20° el.	400	19	5%

18.6 SOME POSSIBILITIES FOR FUTURE EQUIPMENT

Some of the following suggestions have been tested in Service equipment, in which case reference is made to the Army-Navy designation of the equipment; others are ideas on paper only.

18.6.1 Components

ANTENNA

The necessity for large search and track coverage for both offensive and defensive AGL systems has been discussed in Section 18.2. All antennas designed to date have had to perform both of these functions, and compromises have been made in size, weight, search and track coverages, or period. Future compromises of this sort may endanger the value of the equipment. While it may not be impossible to design a single ideal antenna, it is certainly much more obviously possible to design two antennas, one for search and one for track, which will meet all performance requirements. Antennas designed at K band might come close to meeting the size and weight requirements as well. For the track antenna a rotating dish design would be best at this short wavelength, and for the same performance the dish need be only about one third the diameter of the corresponding X band antenna. Consequently, the conical-scan motor could be less powerful and therefore lighter. The azimuth-elevation drive motors could be smaller because the antenna need no longer search, and their operation would be infrequent and of short duration. Furthermore, if the antenna were mounted on a turret and therefore need only be capable of relative angular displacement equal to the lead angle, an additional reduction in size and weight could be made from that of a corresponding antenna which must search as well as track. The track antenna for night-fighter work would, of course, use a larger reflector to obtain a narrow beam for low altitude work than would be required for the track antenna for a bomber defensive system.

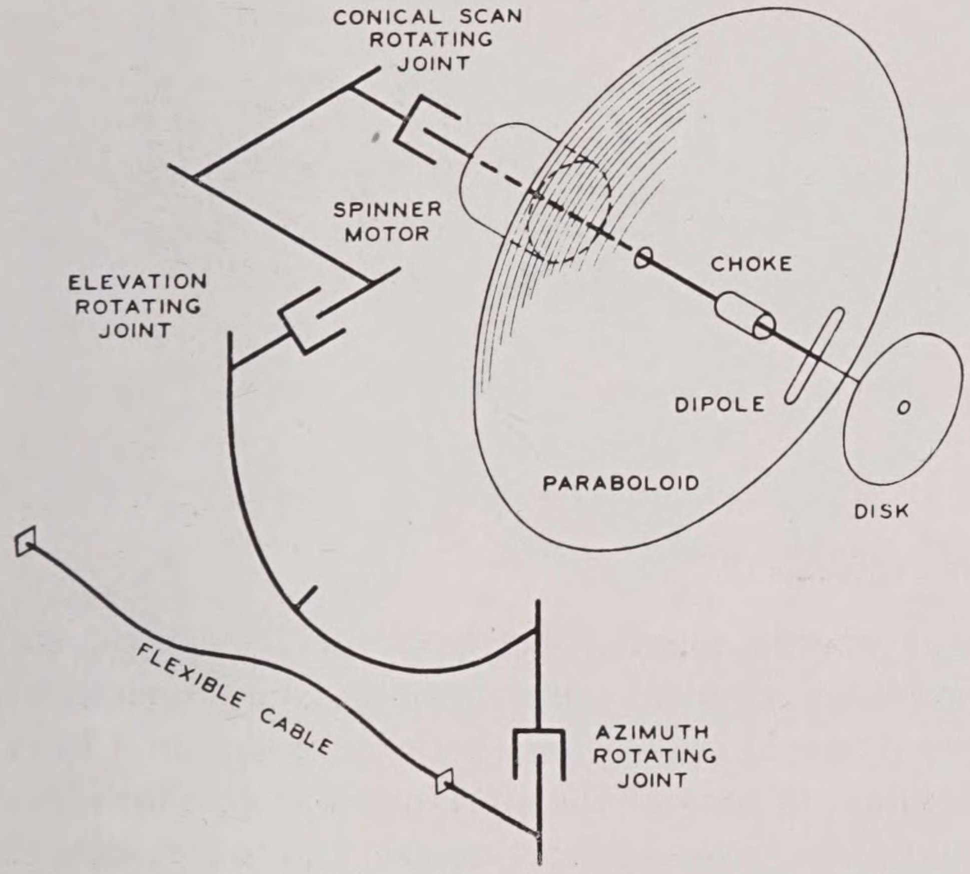


FIGURE 10A. AN/APG-1 antenna and transmission line (schematic).

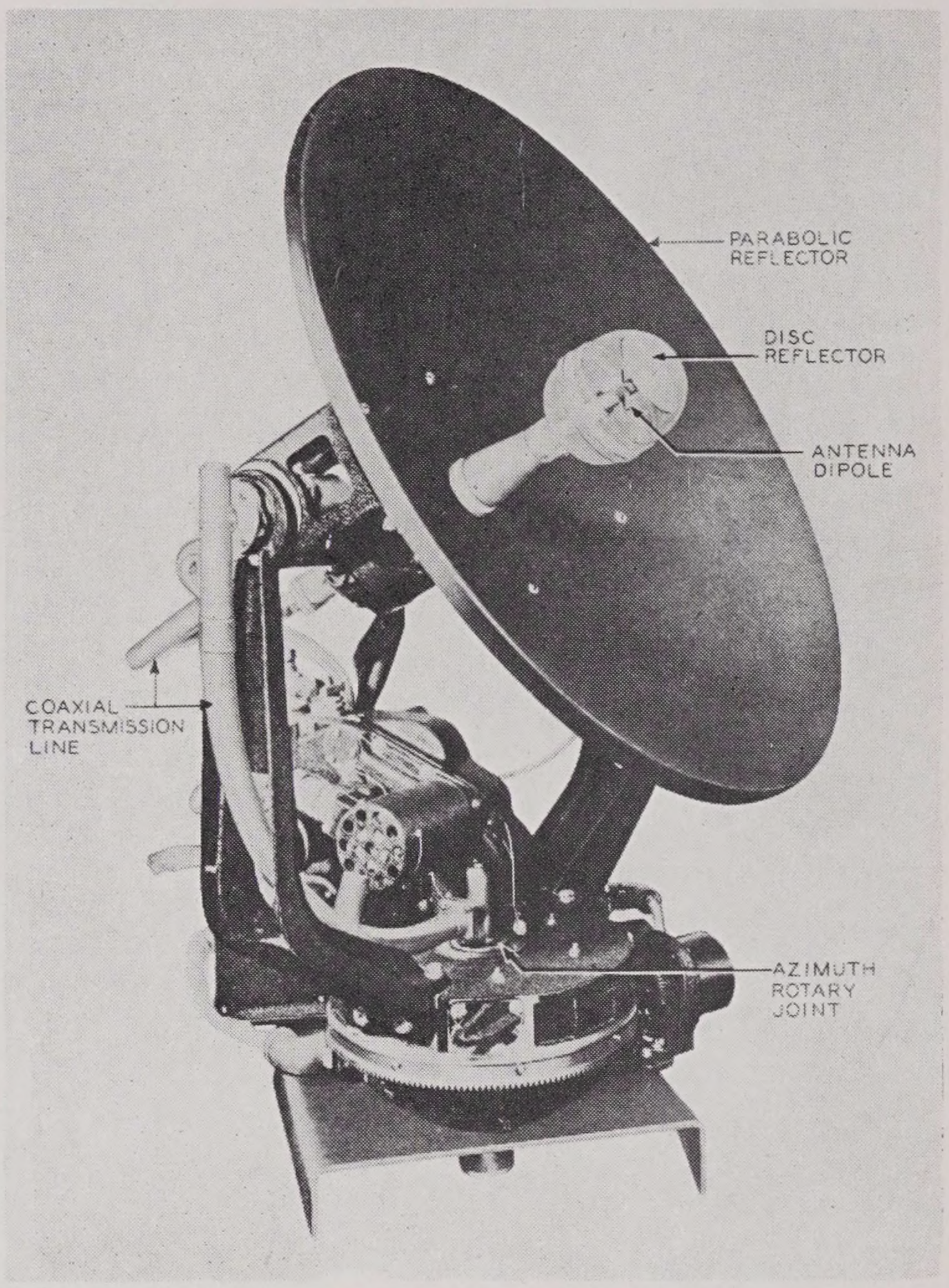


FIGURE 10B. AN/APG-1 antenna.

The search antenna must have a beam which is fairly narrow in the *E* and *H* planes to provide angular discrimination on airborne targets. It would be desirable to design the search antenna so that it would permit indications suitable for navigation and bombing as well as for aerial search. Assuming that hemispherical scan is desired of the search antenna, the approach to the problem may be made in two ways. An antenna may be patterned after an existing one such as the AIA spiral scan antenna (see Chapter 15), in which case the nod angle would be increased to ±90 degrees. The second approach is to design an entirely new type of antenna. Figure 15 illustrates this. The antenna and housing comprise one integral unit. They rotate at fairly high speed in the slant plane (axis *A*); the slant plane is rotated slowly in comparison (axis *B*). The maximum ratio of high speed rotation to low speed rotation is equal to 360 degrees divided by the beamwidth (in degrees). The antenna housing contains, in addition, the high-speed motor drive and gear box and the necessary

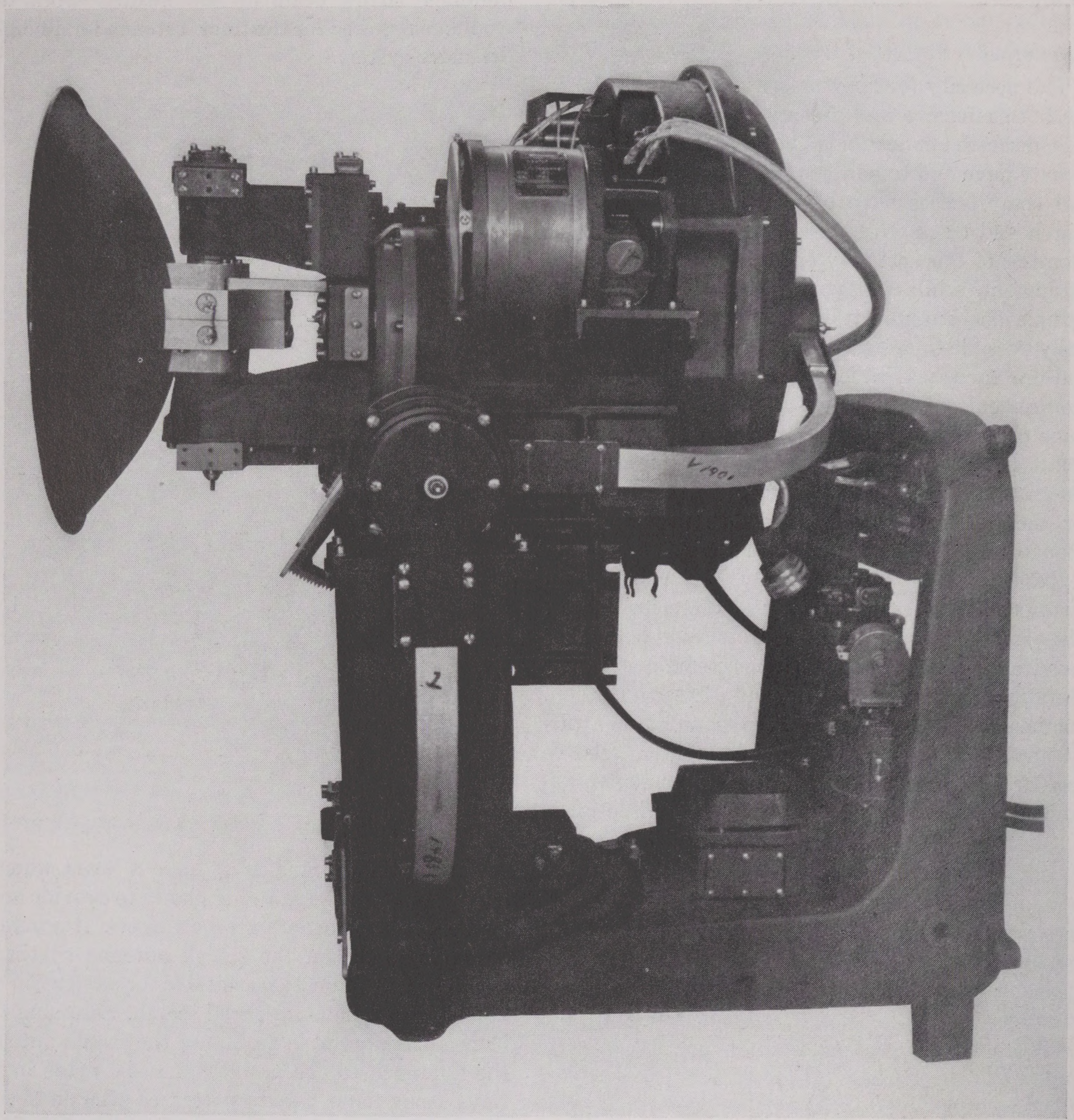


FIGURE 11. AGL-2 antenna.

potentiometers for delivering position information to the indicator. This antenna could be installed either outside or inside the airplane. Periods of about 1 sec could be achieved with both antennas, although with hemispherical coverage very short periods are not necessary.

Rapid television-scan antennas [20, 55a] operating at wavelengths of the order of 0.6 cm have been proposed for use as AGL tracking antennas in offensive systems. While the use of such antennas would present special angular track circuit problems, such problems are not insurmountable. With such antennas it would be possible, if the target were a heavy bomber, to present the airplane silhouette for identification purposes at short ranges, and to forewarn the operator or pilot of evasive action by the target.

INDICATION

The two search antennas discussed above present special indicator problems. If a normal type B indicator is used, a large part of the search volume in the lower part of the hemisphere (assuming the center of coverage to be horizontal) will be lost because of ground echoes and screen persistence. This undesirable condition might be circumvented by use of a variable range gate generated in such a fashion as to blank out the indicator short of the range to ground for the instantaneous positions of the antenna, as illustrated in Figure 16. The B scope would then indicate all targets above a certain altitude only, except for strong off-axis ground targets. For a search antenna which rotates in the slant plane, the range to the altitude below which the indicator is blanked is given by $(h-a)/\cos\alpha\cos\beta$, where $(90-\alpha)$ degrees is the depression angle of the slant plane, β the angle of search in the slant plane, h the altitude of the airplane, and a the search altitude. The generation of a d-c voltage proportional to this quantity to be delivered to the indicator sweep generator for the purpose of obtaining a blanking gate would be a relatively simple matter. It would be necessary to shorten this range gate for large depression angles because of increased signal return from ground targets off the axis of symmetry of the main lobe, unless the use of expanded gain were to make such a device unnecessary. A type C indication would be a useful adjunct, if the variable range-blanking gate and expanded gain were incorporated into the system.

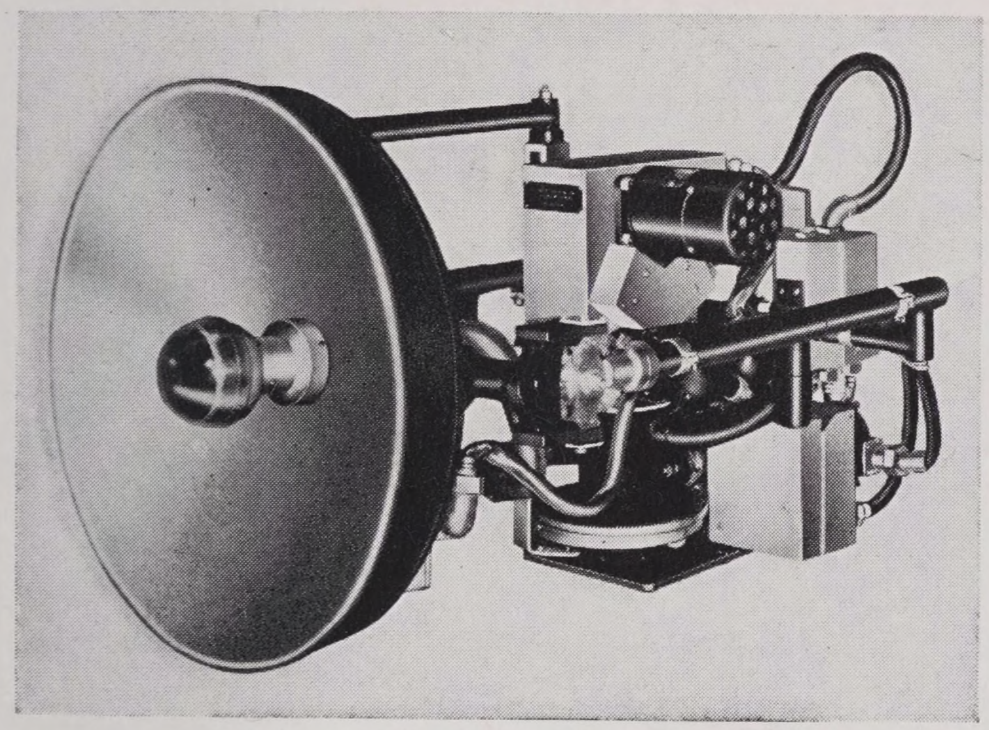


Figure 12. AN/APG-3 antenna.

Expanded Gain

Expanded gain, used in AN/APG-13B (see Section 20.5), is the addition of a small portion of the indicator sweep voltage to the receiver gain voltage. It results in a more uniform indication of target brightness on the B scope, regardless of range. Receiver gain is small at short ranges and full on at maximum ranges. Its use with AGL has the following advantages:

1. AGC action need not be so great.
2. There is more uniform target brightness on B scope presentation.
3. It makes possible the use of type C indication, where desirable, by eliminating one of the chief objections to the latter, namely, the inherent low ratio of target brightness to background brightness caused by the piling up of noise.
4. Its use simplifies the problem of gating out ground echoes on the type B search indication as described in "Indication," Section 18.6.1.

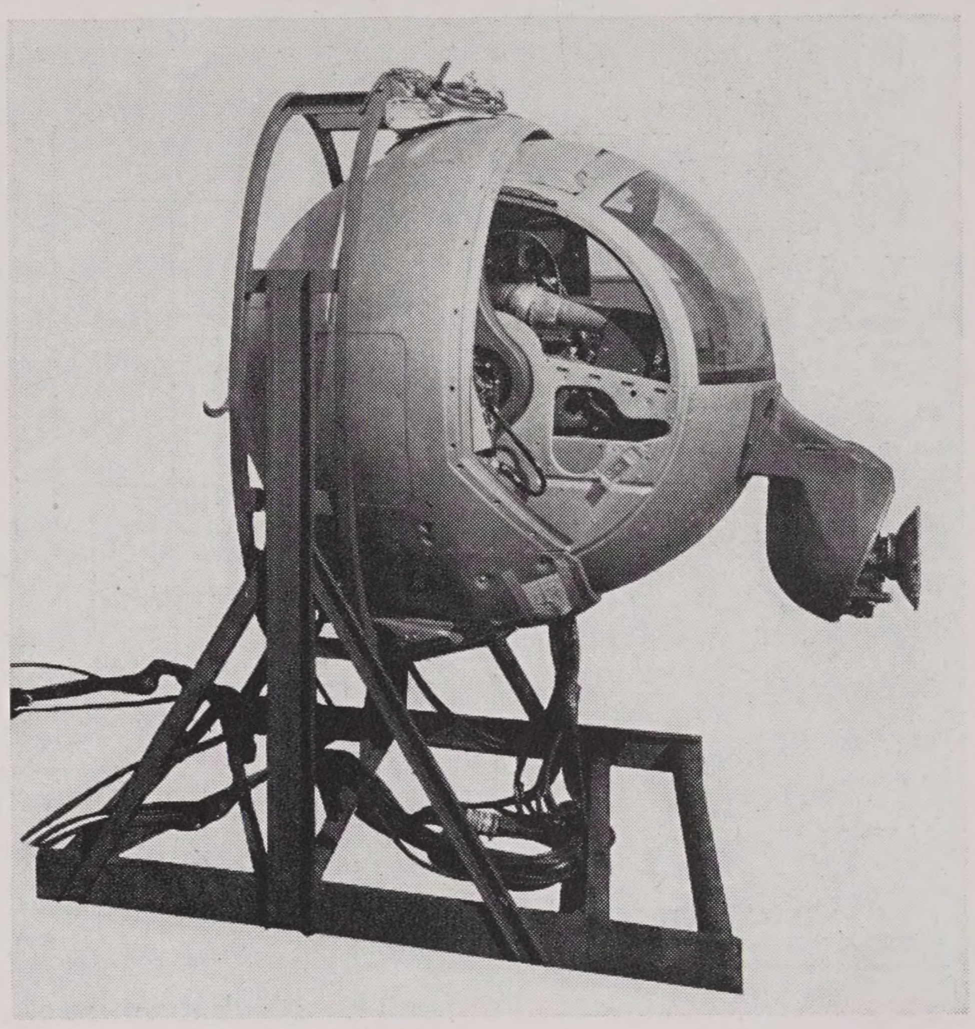


Figure 13. AN/APG-16 antenna mounted on turret.

Automatic Range Search and Lock-on

A modification of circuit design developed for AN/APG-21, *Terry* (Section 20.6), which enables it to search for and lock on unmodulated signals only, would be a useful adjunct to the daytime use of AGL equipment. The modification would consist of permitting the range gate to lock on a slightly modulated echo and therefore not be thrown off if the operator's tracking is erratic. Its use would eliminate one of the present duties of the operator, namely control of the range switch.

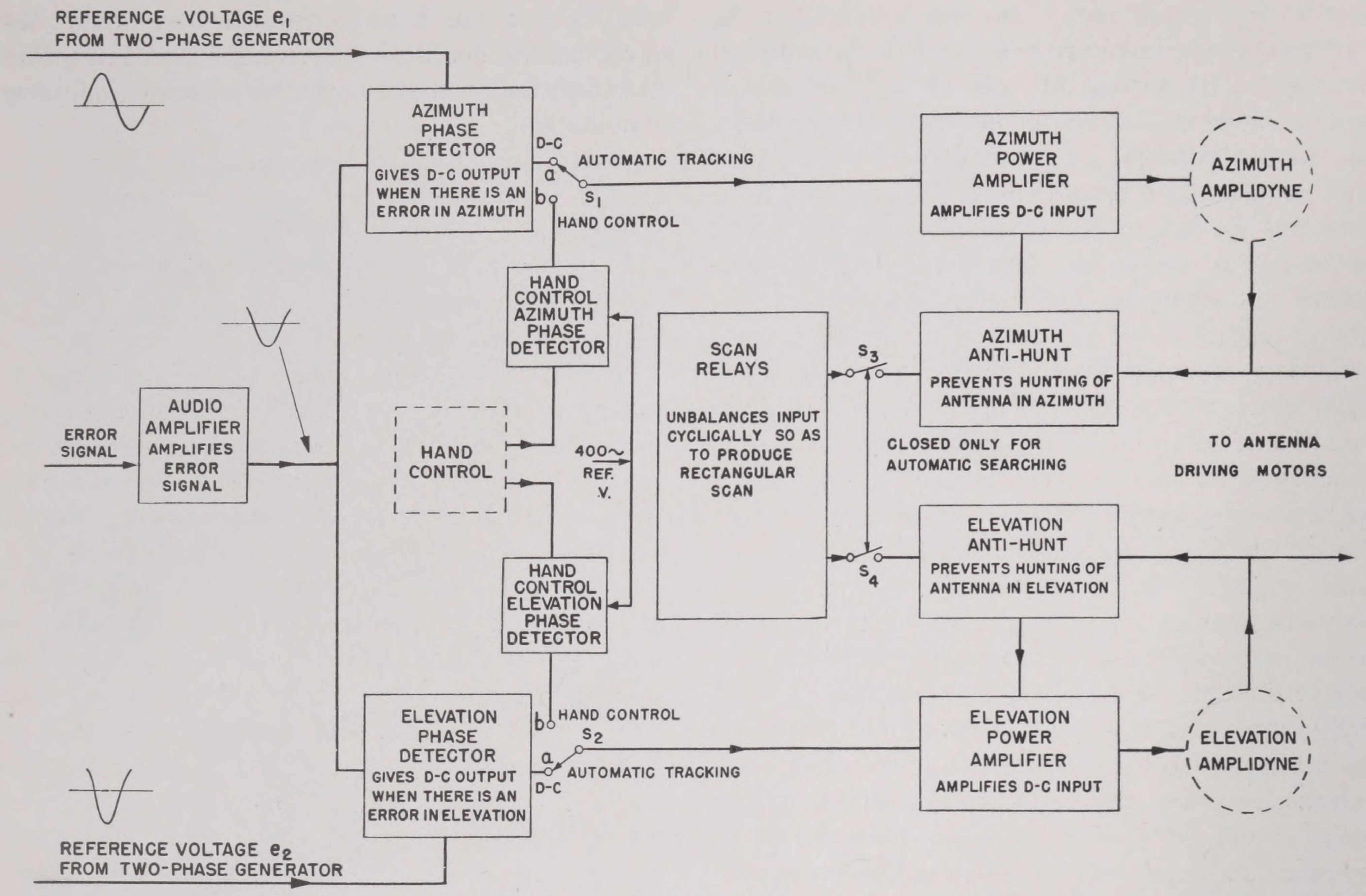

REFERENCE VOLTAGE e_1
FROM TWO-PHASE GENERATOR
AZIMUTH PHASE DETECTOR
GIVES D-C OUTPUT WHEN THERE IS AN ERROR IN AZIMUTH
D-C
a
b
S_1
AUTOMATIC TRACKING
HAND CONTROL
AZIMUTH POWER AMPLIFIER
AMPLIFIES D-C INPUT
AZIMUTH AMPLIDYNE
HAND CONTROL AZIMUTH PHASE DETECTOR
SCAN RELAYS
UNBALANCES INPUT CYCLICALLY SO AS TO PRODUCE RECTANGULAR SCAN
S_3
AZIMUTH ANTI-HUNT
PREVENTS HUNTING OF ANTENNA IN AZIMUTH
ERROR SIGNAL
AUDIO AMPLIFIER
AMPLIFIES ERROR SIGNAL
HAND CONTROL
400~ REF. V.
CLOSED ONLY FOR AUTOMATIC SEARCHING
TO ANTENNA DRIVING MOTORS
S_4
ELEVATION ANTI-HUNT
PREVENTS HUNTING OF ANTENNA IN ELEVATION
HAND CONTROL ELEVATION PHASE DETECTOR
ELEVATION PHASE DETECTOR
GIVES D-C OUTPUT WHEN THERE IS AN ERROR IN ELEVATION
b
HAND CONTROL
S_2
a
AUTOMATIC TRACKING
D-C
ELEVATION POWER AMPLIFIER
AMPLIFIES D-C INPUT
ELEVATION AMPLIDYNE
REFERENCE VOLTAGE e_2
FROM TWO-PHASE GENERATOR

FIGURE 14. Block diagram of AN/APG-1 antenna servo amplifier.

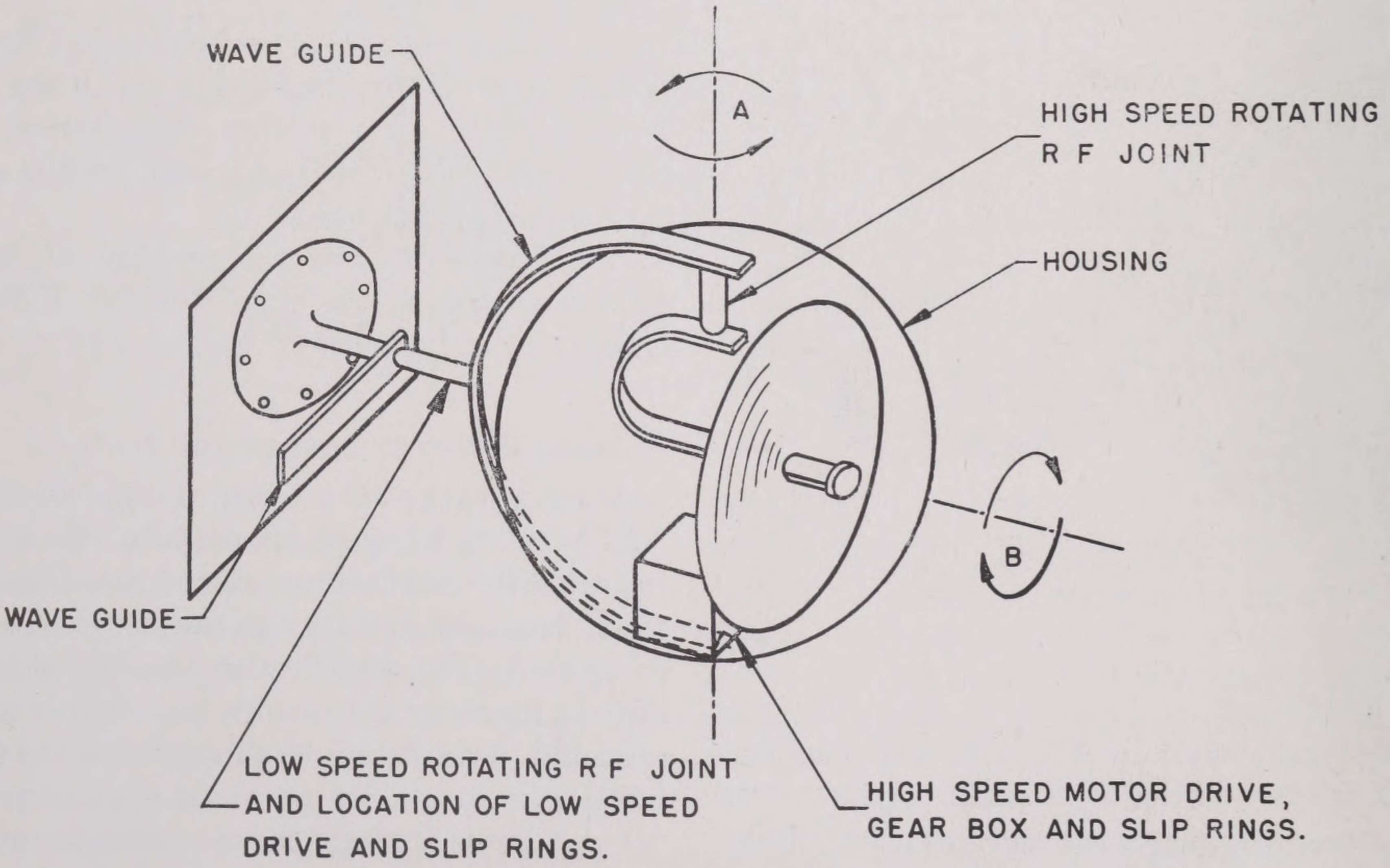

WAVE GUIDE
A
HIGH SPEED ROTATING R F JOINT
HOUSING
B
WAVE GUIDE
LOW SPEED ROTATING R F JOINT AND LOCATION OF LOW SPEED DRIVE AND SLIP RINGS.
HIGH SPEED MOTOR DRIVE, GEAR BOX AND SLIP RINGS.

FIGURE 15. Simplified sketch of hemispherical search antenna assembly.

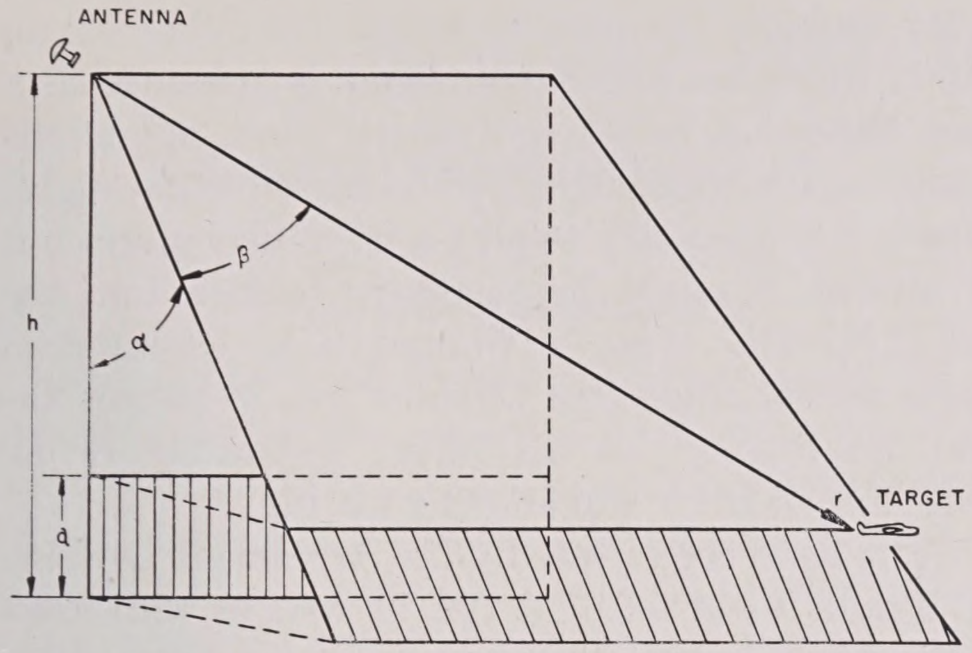

ANTENNA
h
α
β
a
r
TARGET

Figure 16. Avoidance of ground signals by range gating. Indicator is blanked for signals coming from targets whose altitudes are less than *a*. (The target airplane in the figure is at the lowest altitude for which detection would be possible.)

18.6.2 Systems

Defensive Systems

The use of separate antennas for the search and track functions would provide the basis for a centralized radar fire-control system for bomber protection. Two hemispherical search antennas, one fore and one aft, would give a fire-control director the range, bearing, and heading of all airborne targets within the operating radius of the equipment, assuming that variable range-blanking gate and expanded gain (see "Indication" and "Expanded Gain" in Section 18.6.1) are incorporated in the equipment. Tracking antennas placed on each turret, driven by signals from computing sights contained therein or by a central station computer, would provide automatic tracking and deflection shooting.

It might not be necessary to have a complete radar set for each of these tracking antennas, if pairs of turrets were not too far separated. In that event a single r-f head could feed both antennas by having the fire-control director switch the power to the desired one. Indicators would be centralized and would not be needed at the local stations. Uninhabited turrets could be remotely positioned and fired by the fire-control director. Target position information could be transmitted to inhabited turrets in any one of a number of standard methods. Video signals from local systems, channeled to the central indicator, would give the fire-control director a constant check on the operation of local systems. Triggering all modulators at the same time would reduce duplication in indicator circuits, for then two sweep generators, one

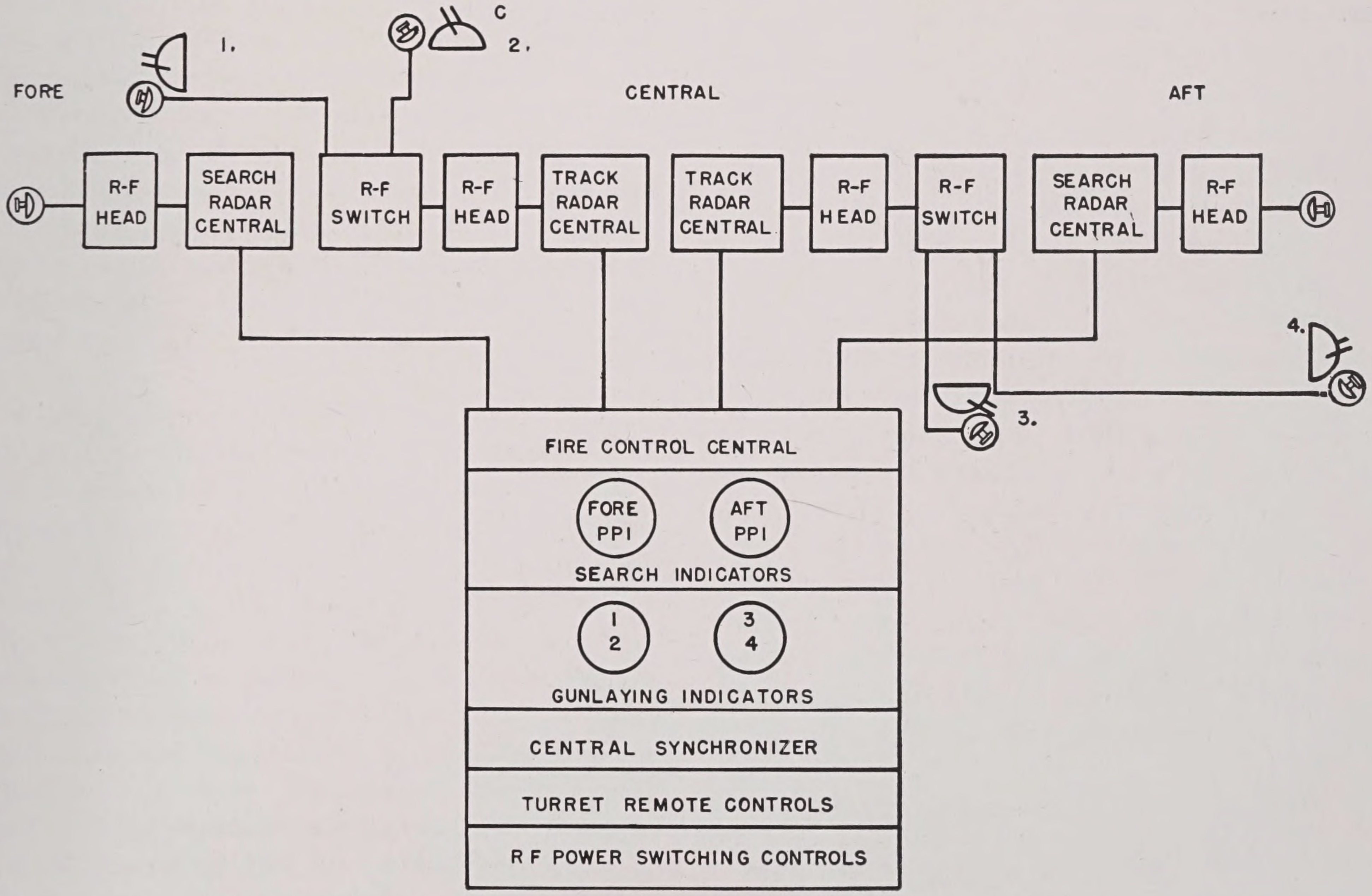

1.
C
2.
FORE
CENTRAL
AFT
R-F HEAD
SEARCH RADAR CENTRAL
R-F SWITCH
R-F HEAD
TRACK RADAR CENTRAL
TRACK RADAR CENTRAL
R-F HEAD
R-F SWITCH
SEARCH RADAR CENTRAL
R-F HEAD
4.
3.
FIRE CONTROL CENTRAL
FORE PPI
AFT PPI
SEARCH INDICATORS
1 2
3 4
GUNLAYING INDICATORS
CENTRAL SYNCHRONIZER
TURRET REMOTE CONTROLS
R F POWER SWITCHING CONTROLS

Figure 17. Central radar control for a possible bomber fire-control system.

short-range, one long-range, could supply all indicator tubes. Figure 17 illustrates the control of a hypothetical armament system.

Offensive Systems

Simplifications in AGL equipment since the design of AN/APG-1 and AN/APG-2 make it entirely possible that a night-fighter pilot could operate it. The pilot would have a remote scope, a control switch, and possibly a target in-out range switch.

With slight modifications in the circuits, a night-fighter AGL system could be made to perform the daytime ground support functions of air-to-ground and air-to-sea attack performed by AN/APG-21 (see Chapter 20). The night fighter would then become a very potent day fighter as well; the system would become a universal AGL radar. Briefly, the modifications required are as follows.

1. The addition of rejection circuits in the range unit to permit locking in range on unmodulated signals only, thereby causing the range unit to track the target toward which the pilot is aiming his sight.
2. Tie-in with a computer or a computing sight, such as the Draper-Davis S-9, delivering the proper depression angle information to drive the scanner. The error signal would not be used in these operations.

By enabling the pilot to switch his indication to one in which the radar error signal is presented as a spot deflection or its equivalent, these operations against sea targets might well be performed at night. Where it is necessary to pick a particular target out of several, it might be necessary to introduce the AN/APG-13B type V presentation, conical-scan angle versus range (see Chapter 20), to permit the pilot to line up on his target accurately before switching to track and starting his run.

Tests have been made by the Armament Division at Wright Field on SCR-702-T1 tied in with *automatic flight control equipment* [AFCE]. The equipment was installed in the XA-26A airplane. The AGL equipment caused the XA-26A to follow the target automatically. These tests are significant when one considers that the night fighters' prey of the future would in all likelihood be an ultra-fast jet-propelled airplane or a guided missile wherein split-second timing of a degree beyond human capabilities might be required to make successful kills. It would be possible to tie in automatic-following equipment and computers with AFCE to make a completely automatic interception and to fire automatically or launch with the proper deflection angle the lethal missile — be it bullet, shell, proximity-fused bomb or rocket, or the airplane itself.

Chapter 19

MANUALLY DIRECTED RADAR GUNSIGHTS

19.1 GENERAL CONSIDERATIONS

19.1.1 Type of Application

Some military requirements for fire-control radar cannot be met at the present state of radar development with the fully *automatic gunlaying* equipment [AGL] discussed in Chapter 18. Such requirements take the form of restrictions of weight, volume, and complexity. If reduced performance is tolerable, the restrictions can often be met by a manually directed radar gunsight. The general name for any radar sight of this class is *airborne gunsight* [AGS]; the particular system discussed below is AN/APG-15 [35] (see Section 19.2). In general, such a system finds application only when the more completely automatic equipment would be too large, too heavy, or too complex. The following examples of these conditions can be given.

Shipborne Night Fighters

In general, the number of types of aircraft used on carriers is kept to a minimum and, as a result, it is highly desirable to use standard single-place fighters for both day and night fighting (see Chapter 14). In carrier fighters, therefore, it is impossible to use radar equipment that requires a special operator; likewise it is important that the equipment be small and lightweight. As a consequence of these considerations the night-fighter radar for carrier-based fighters is of the manually directed type, that is, the pilot uses his aircraft as a gun mount and acts as a biomechanical servomechanism between the radar indication and the guns.

Land-Based Night Fighters

An airplane like the P-61 with an upper remote turret is admirably suited to completely automatic gunlaying. However, if the plane has *aircraft interception* [AI] equipment like the SCR-720, an auxiliary radar is needed to make the turret effective. Such a radar could be of the manually directed type, since neither long range nor search is a requirement. This type of combined installation is somewhat more flexible than a straight AGL installation, allowing continuous long-range search while the manually operated radar handles near-by targets. However, the disadvantage of such an installation is that in addition to requiring an operator, the lightweight form as developed in World War II is less accurate than AGL.

Heavy Bombers

As an adjunct to a fire-control system designed for optical tracking, a manually operated radar gunsight is more feasible than a complete AGL system. Usually the installation of an AGL system requires several modifications to existing bombers, whereas a manually directed radar gunsight requires few, if any, modifications. For little more than the cost of adding radar ranging, a radar gunsight can be obtained. However, the decision as to the type of equipment to be used is definitely a compromise between accuracy on the one hand and weight, bulk, and complexity on the other. Manually directed radar gunsights found most applications in tail defense of heavy bombers, in theaters where enemy night fighters were not very aggressive.

19.1.2 Methods of Achieving Simplicity

Component Packaging

One of the most direct methods of achieving simplicity is to use small, individually cased components. For example, the *lighthouse tube transmitter and receiver* [LHTR] (see Section 20.2) is admirably suited to such systems. The LHTR contains the modulator and r-f components of the transmitter, r-f components and i-f strip of the receiver, and power supplies. This packaging facilitates installation and maintenance (see Section 5.1). Also, the ranging or timing components, or the indicating components can be packaged together. By such functional packaging the system itself is readily adapted to different installations. By standardizing the functions of such units an additional advantage is gained in that each component can be designed to give the desired performance of its function, that is, one transmitter-receiver design can be substituted for another if greater range, different wavelength, etc. are desired; or one range unit may be substituted for another if, for example, different range accuracy or range sweep is desired.

Type of Indication

In almost all radar sets it is necessary to convert the electrical radar information to an optical presentation. Such conversion components, called indicators, are often very complex and consequently require considerable power and space. To simplify an indicator it is necessary to sacrifice some desirable qualities such as low distortion or multiple target presentation. For instance, in the AIA equipment the indicator allows a choice of B or G type, the B presentation (range versus azimuth) being used for search and the G presentation (see Section 15.1.9) for gun pointing. In the AGS equipment the indicator is type G. In both the AIA and AGS systems the amount of information presented on the indicator is a compromise between simplicity and component size.

Type of Antenna

The type of indication used is closely allied to the antenna design and simplified indicators probably save more in the antenna than in the indicator components. Antenna design is extremely important, especially when the antenna must be mounted externally and thereby contributes to drag. The mounting of a large antenna may also require changes in the design of the aircraft, so it is generally worth while to keep the antenna small and the mounting arrangements simple.

Perhaps the best illustration of this design principle is the AGS antenna used in the AN/APG-15 system.[35] As in all current airborne gunlaying systems, the antenna performs a conical scan (Figure 2, Chapter 18); for simplicity this system employs a rotating paraboloid with a fixed feed. The phase reference generator is coaxial with the rotating member and is essentially an electric switch. The whole antenna assembly is a ball-like package, 16 in. in diameter and weighing 20 lb. Mounting is accomplished by connection to four existing bolts in the B-29 tail turret. In this design high pointing accuracy is sacrificed for greater coverage; since there is no independent search scan the beamwidth and conical scanning must be broad enough to give sufficient coverage while allowing reasonable pointing accuracy.

Type of Antenna Mounting

As indicated in the paragraph above for the AN/APG-15 case, considerable complexity is eliminated by mounting the antenna directly to the guns. This is readily accomplished for a small unit such as is used in the AGS or *airborne range only* [ARO] systems. Obviously this mounting arrangement is not always possible; but, where possible, it greatly simplifies installation of the equipment.

19.1.3 Methods of Achieving Simple Computer Tie-Ins

The use of manually directed radar systems in conjunction with lead-computing mechanisms has not found general application. However, such systems have been studied and some experimental installations made. Computer tie-ins fall into two distinct classifications: systems in which only the radar range information is fed to the computer, and systems which permit computed blind fire. Figure 1 shows a block diagram of these two classifications as well as a basic radar system with no computer tie-in. These diagrams show the fundamentals irrespective of type of installation or computer; obviously the mechanization of such systems is dependent upon both.

Sights for Fixed Guns

For fixed-gun fighters the second type of computer tie-in is made, if any tie-in is made at all. The problems of flying an airplane by means of a spot error indication (or any other angular high-precision indication) are so severe that blind attacks are, in general, limited to straight tail attacks. For such attacks no deflection is necessary and, consequently, no computer is necessary. For daylight operation, however, radar range is far superior to optical range, and the use of radar range greatly enhances the effectiveness of the fighter.

Director-Type Computer

In aircraft with fire-control systems like those of the P-61 or B-29 the computers are of the director type, that is, target position and rate are measured independently of the gun position and rate (see Section 21.3.1). It is reasonably straightforward to connect a manually directed radar set into this type of gunlaying system. By mounting the antenna directly to the guns, but allowing a few degrees (approximately 15 degrees for caliber 0.50 guns) of independent motion, the radar axis can be offset from the gun direction by the amount of the lead angle. Such an arrangement is efficient since it requires only small slow-speed servomechanisms to position the antenna with respect to the guns, gross positioning being done by the large turret servos. Radar range is fed into the computer.

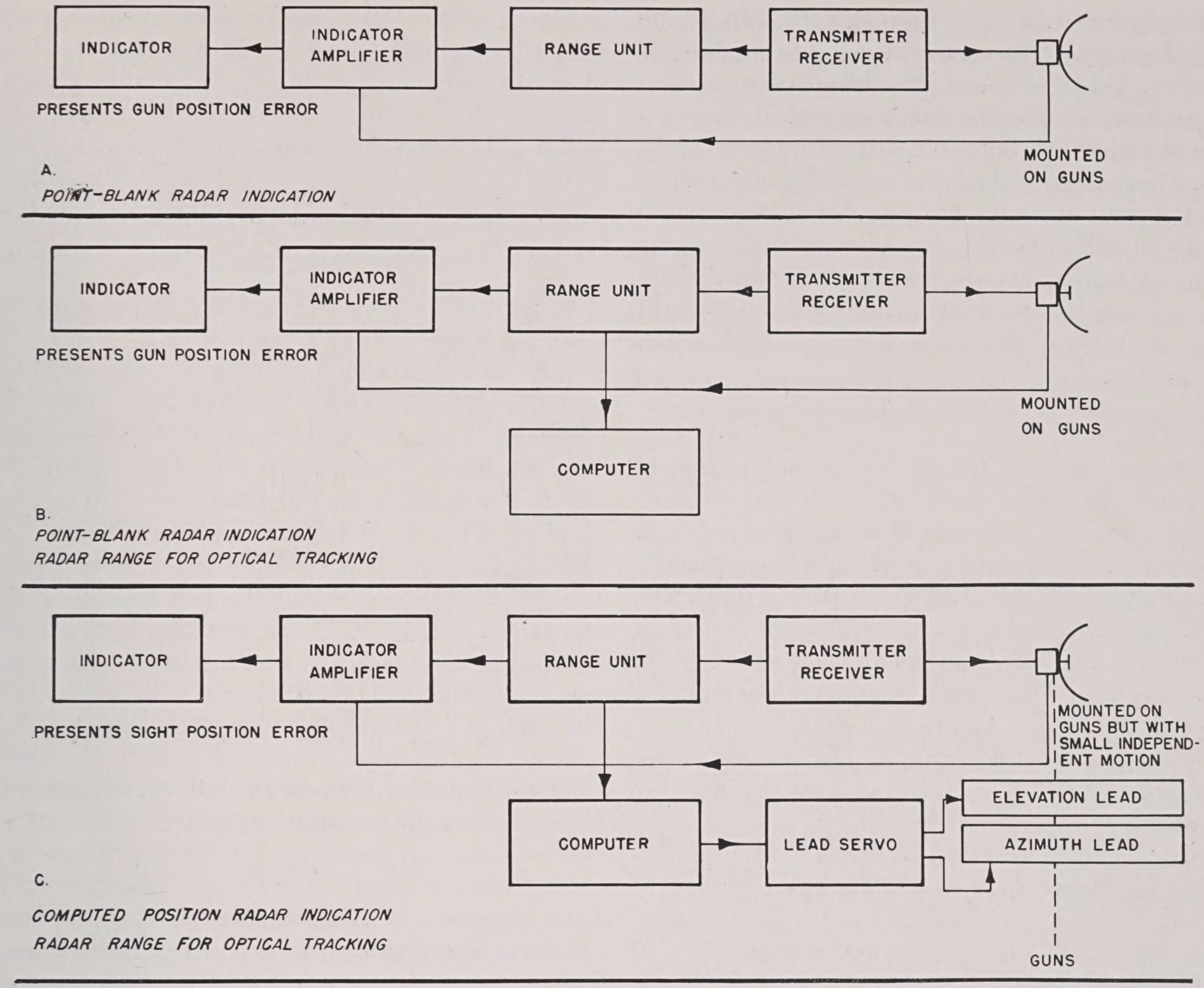

INDICATOR
INDICATOR AMPLIFIER
RANGE UNIT
TRANSMITTER RECEIVER
PRESENTS GUN POSITION ERROR
MOUNTED ON GUNS
A.
POINT-BLANK RADAR INDICATION
INDICATOR
INDICATOR AMPLIFIER
RANGE UNIT
TRANSMITTER RECEIVER
PRESENTS GUN POSITION ERROR
MOUNTED ON GUNS
COMPUTER
B.
POINT-BLANK RADAR INDICATION
RADAR RANGE FOR OPTICAL TRACKING
INDICATOR
INDICATOR AMPLIFIER
RANGE UNIT
TRANSMITTER RECEIVER
PRESENTS SIGHT POSITION ERROR
MOUNTED ON GUNS BUT WITH SMALL INDEPENDENT MOTION
ELEVATION LEAD
COMPUTER
LEAD SERVO
AZIMUTH LEAD
C.
COMPUTED POSITION RADAR INDICATION
RADAR RANGE FOR OPTICAL TRACKING
GUNS

FIGURE 1. Block diagrams of manually directed gunsights.

DISTURBED-RETICLE SIGHTS

Effecting a complete tie-in with a computer like those commonly used in inhabited turrets is fairly difficult. Suppose that the radar antenna is mounted rigidly on the turret and boresighted with the gun bore axis and that the scope presentation is type G. Then the target signal is displaced from the center of the G scope by an amount λ corresponding to the angle L' between the gun bore axis and the line of sight to the target. The displacement λ is ordinarily not a linear function of L', although for angles L' less than 4 degrees a satisfactory linear approximation to λ can be made. Suppose, next, that the sight case is mounted on the guns so that the computer measures angular rates of the gun line. Then, to effect a complete tie-in of radar and computer it is necessary to set up a relation between λ and the computed lead L such that $L = L'$. For instance, in the British AGL-T the radar presentation was superimposed on the sight reticle and the matching of L to L' consisted of positioning the guns so that the radar target-pip coincided with the center pip of the sight reticle. This tie-in introduced problems of operational stability which are discussed below. Aside from stability problems the sighting system had errors whenever the lead L was sizable, as a result of both the nonlinearity of the relation between the scope target-pip deflection λ and the actual lead L', and the variability (static instability) of the scope sensitivity.

The British Gyro Gunsight Mk II-c (upon which the U. S. Navy Mk 18, 21, 23, and the U. S. Army K-14, -15, -17 were based) was the sight member of the AGL-T combination. In this sight (and its derivatives) the lead is computed optically and there is no means provided for delivering a mechanical or electrical lead signal. For those computers from which a mechanical or electrical lead signal output can be obtained, it is possible to provide a servo-driven antenna which can be offset from the gun axis by the amount of the computed lead (just as in director systems). This overcomes any difficulties caused by the nonlinearity of scope deflection and by the variation in scope sensitivity, but introduces servo problems. These servo problems are not difficult to solve, but the related engineering problems were sufficiently complex that it was not considered worth while to attempt their solution during World War II. Instead, attention was directed to the more immediately available point-blank system described in Section 19.2.

Stability Problems

As indicated above, the use of a manually directed radar gunsight with a disturbed-reticle lead-computing sight presents problems of operational stability. A disturbed-reticle sight is said to be operationally stable if, when the gun is given a small but quick jerk (by a jerk of the gun we mean a discontinuity in velocity) in some direction the reticle is jerked in the same direction; if the reticle is jerked in the opposite direction the sight is said to be unstable.[58, 89]

The AGL-T was the only system of this composite type used in World War II, and as originally installed it proved to be operationally unstable, in spite of the fact that each component was stable in itself. The following discussion of the problem is based upon a report by Dr. C. W. Gilbert of the British Gunnery Research Unit.[139] The problem is considered first in mathematical terms.

Consider a fixed direction in space, and let γ, ρ, σ, and τ be the angles made with it by the gun line, line to apparent radar target, sight line (line to moving reticle spot), and line to the actual target, respectively. The task of the gunner is to keep the radar and reticle spots, which he sees, in coincidence (the gunner is in total darkness, otherwise). This has the effect of keeping ρ equal to σ. It will be noted that the computed lead L [neglecting the ballistic term β of equation (1), Chapter 23] is $\gamma - \sigma$; the lead actually being taken by the guns, L', is $\gamma - \tau$; and the deflection of the radar scope spot λ is $\gamma - \rho$.

The differential equation for the lead computing sight [58] may be written as

$$(1 - a)\, u\, (\dot{\gamma} - \dot{\sigma}) + (\gamma - \sigma) = u\dot{\gamma} \qquad (1)$$

where u is the time of flight and a is the sight parameter. (Dots indicate time derivatives.) This is equivalent to equation (1), Section 21.3.1, provided the ballistic term β in the latter is neglected. Solution of this equation shows that the sight reticle comes to rest, after a sudden motion, with the time constant $(1 - a)u$ (see Section 22.2.3, "Errors in Optical Range Determination") provided that $a < 1$. (For $0 < a \leqslant 1$, the sight would be operationally unstable; for $a < 0$ the sight is operationally stable.)

For the radar target-pip, the differential equation

$$k\,(\dot{\gamma} - \dot{\rho}) + (\gamma - \rho) = \gamma - \tau \qquad (2)$$

will apply, where k (> 0) is the time constant for the damping of the motion of the spot.

Now we inquire how it happens that the combined system can be unstable when both sight and radar are stable (a negative and k positive). If it is assumed that the operator tracks perfectly, that is, keeps the reticle pip on the radar pip, then $\sigma = \rho$. To test for stability of the combined system, set $\rho = \sigma$ and then eliminate σ from the two differential equations, obtaining an equation relating the gun position γ and the target position τ. If this equation is that for a damped motion, then the gun will follow the target and the system will be stable.

$$-\,ku\ddot{\gamma} + (-a)\, u\dot{\gamma} + \gamma = (1 - a)\, u\dot{\tau} + \tau. \qquad (3)$$

This equation will represent damped motion only if the roots of the quadratic equation

$$-kux^2 + (-a)ux + 1 = 0 \qquad (4)$$

have negative real parts, which requires that the coefficients of x^2 and x both be positive. Since k is always positive, the coefficient of x^2 must be negative, and therefore the system is operationally unstable.

In physical terms this means that if there is any optically appreciable lag in the motion of the radar spot, the gunner will have to move the turret in the opposite direction from that of the target motion in order to make the two spots come together; but when he has done this, the spots will immediately drift apart again, and his only chance of tracking is to make a series of trial motions, waiting for equilibrium each time. This would obviously be impossible for a target with a high angular rate.

The instability could be removed by either (1) greatly reducing the time lag k of the radar or (2) increasing a so that the sight line would follow the gun line more closely, or (3) combinations of (1) and (2). In practice, neither (1) nor (2)was feasible. The solution adopted was to feed onto the display, in series with the radar error voltages, additional voltages proportional to the acceleration of the guns in elevation and of the turret in azimuth.[88a, 139–141]

19.1.4 Identification

One of the most serious problems in the design of any gunlaying set is identification of a target as friend or foe. The problem is equally serious whether the gunlaying set is designed for defensive installations in bombers or offensive installations in fighters. However, the problem does have different aspects for the two applications. In general, the burden of identification rests with the attacking aircraft, so it is rather more important for the fighter to identify its target correctly than for the bomber to identify its target correctly. This is based on the assumption that if a fighter attacks a friendly bomber, the net loss is smaller if the fighter is shot down than if the bomber is shot down. From the fighter's point of view, the identification equipment must be reliable and secure. Reliability can be obtained by proper engineering design; but security depends more on flexibility of design and inherent design characteristics.

Identification without Special Equipment

Under certain operational conditions it may be possible to accomplish identification without the use of special equipment. Such identification is usually accomplished by the employment of special tactics or procedures. For instance, this system is applicable to the identification of enemy night fighters by unescorted bombers. If the bombardment aircraft contains manually directed fire-control equipment, or automatic fire-control equipment, and can determine when an aircraft is trailing the bomber, it is generally sufficient to establish that the detected aircraft is trailing and is not in the line of fire by mere chance. This can be accomplished by an abrupt change of course. If the detected aircraft follows this maneuver, it can reasonably well be assumed to be a radar-equipped enemy night fighter; whereas if the detected aircraft does not follow this maneuver it can reasonably well be suspected of being in the cone of fire by chance. As mentioned in the paragraph above, this means of identification is of practical value only in theaters where the burden of identification rests with the attacking airplane.

Beacon Responders

In most cases it is necessary to establish general, bilateral identification, and to this end, beacon challengers and beacon transpondors have been developed to a high degree of perfection.[57] In these systems the identification equipment is a separate and distinct electronic component and interconnects with the fire-control equipment only to the extent necessary to give target identification. A discussion of the technical features of the beacon systems used for identification is not within the scope of this chapter; such systems do exist and work satisfactorily. The biggest single objection to this type of identification is in its inflexibility. Since, in any given theater, it is necessary to install a very large number of these systems, it is very difficult to change if the security is questioned. As far as the parent radar system is concerned it is reasonably easy to standardize input and output for the identification unit, such standardization permitting different types of beacon units to be used without modification to the parent radar sets.

Propeller Modulation

An effective system of identification can be instrumented on the basis of the propeller modulation of the detected aircraft. A system utilizing this principle, the AN/APX-15, was designed and used. This system is particularly applicable to the fire-control radars because they are, in general, designed to permit careful modulation studies of each individual echo return. Such a system requires thorough and precise knowledge of all of the enemy and friendly aircraft expected to be encountered. A thorough analysis of this data may show a general difference in the modulation characteristics of friendly and enemy aircraft. If this is true, the difference in the modulation can be used as a basis for identification.

19.2 SYSTEM AN/APG-15B

The AN/APG-15B system is a manually controlled radar gunsight mounted on the tail turret of a B-29 aircraft for defensive fire control against enemy night fighters.[35] It is taken as a sample system because it demonstrates most of the design considerations discussed in Section 19.1. The AN/APG-15B was added to the B-29 fire-control system after the fire-control system was in large-scale production. For this reason, it was designed to require the least amount of installation engineering and fire-control system modification. The radar has three distinct functions: (1) to act as tail warning when the B-29 is flying under conditions of restricted visibility, (2) to allow reasonably accurate blind fire, point-blank, under conditions of restricted visibility, and (3) to supply, automatically, accurate radar range to the fire-control computer under conditions suitable for optical tracking. Although it would have been desirable, this system was not designed to permit computed blind fire by the turret on which the antenna is mounted. This would have introduced considerable additional complexity into the system, and it was felt that point-blank fire was adequate for most attacks. However, a simple adjustment of the B-29 system makes it possible to give a computed lead to a different turret from that on which the antenna is mounted. Such an arrangement was being tested at the conclusion of World War II. In this, the lower aft turret delivered computed fire while the tail turret delivered point-blank fire.

In conjunction with the AN/APX-15 identification equipment, the system is able to identify the target as a B-29 or other type of airplane. In the operations in which such equipment found general use, long-range bombardment of the Japanese homeland, this identification was sufficient. The only friendly airplanes over the Japanese empire under conditions of restricted visibility were B-29's.

19.2.1 Arrangement of the System

Figure 2 is a block diagram of the AN/APG-15B and AN/APX-15 equipment. The antenna assembly is mounted directly on the tail turret and harmonized with the guns so that the radar axis remains parallel with the boresight for all turret positions.[32] It is connected to the receiver-transmitter by a flexible r-f cable and to the junction box for power and phase reference voltages. The receiver-transmitter is an individually cased, self-contained unit which contains the complete transmitter and receiver, and power supply. The transmitter operates on approximately 2,700 mc and generates approximately 1.5 kw of radio frequency in a 0.7 μsec pulse with a recurrence frequency of approximately 1,400 per sec. The range unit is an individually cased unit containing all the circuits necessary for detecting a target echo

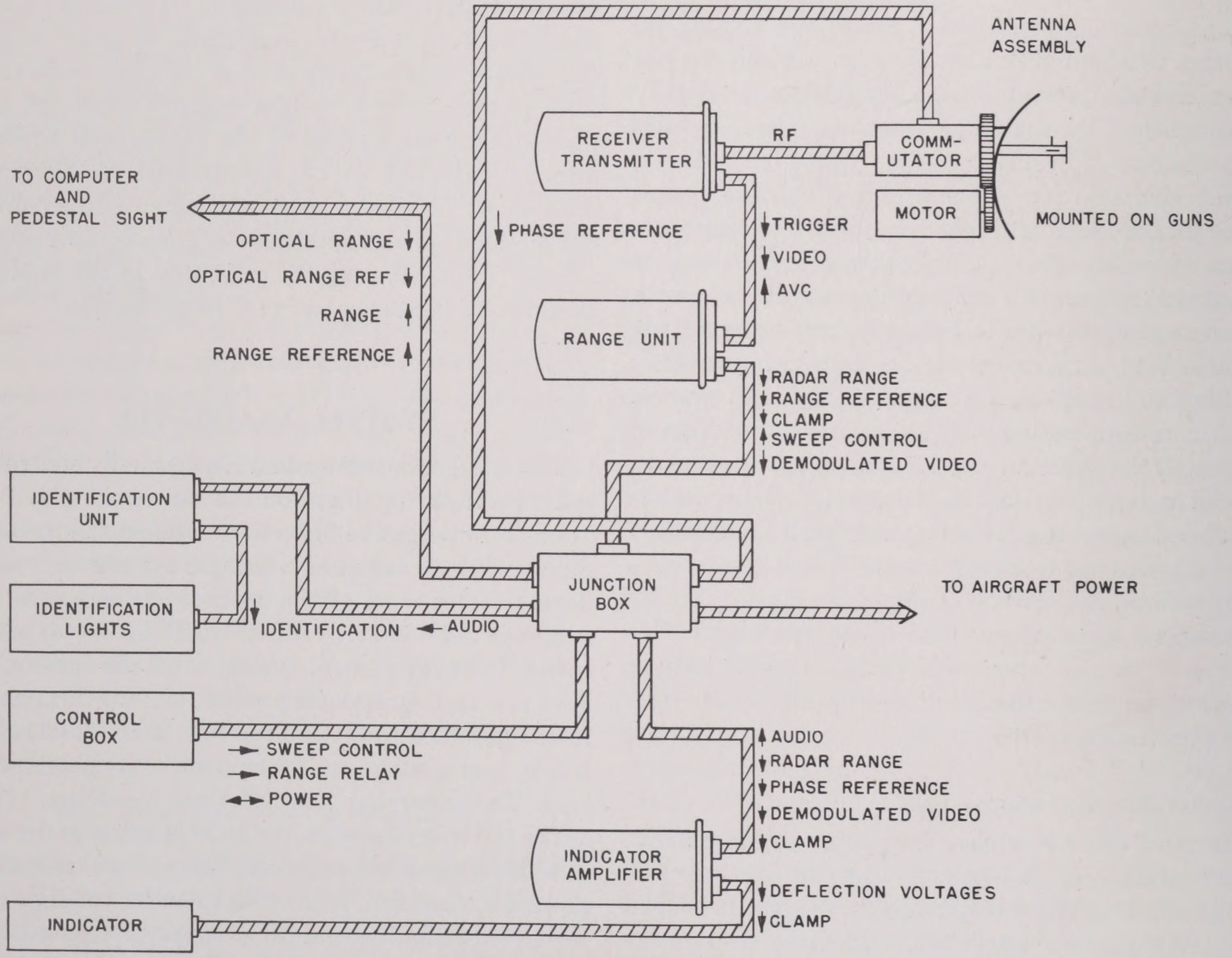

ANTENNA ASSEMBLY
RECEIVER TRANSMITTER
RF
COMMUTATOR
MOTOR
MOUNTED ON GUNS
TO COMPUTER AND PEDESTAL SIGHT
OPTICAL RANGE
OPTICAL RANGE REF
RANGE
RANGE REFERENCE
PHASE REFERENCE
TRIGGER
VIDEO
AVC
RANGE UNIT
RADAR RANGE
RANGE REFERENCE
CLAMP
SWEEP CONTROL
DEMODULATED VIDEO
IDENTIFICATION UNIT
IDENTIFICATION LIGHTS
IDENTIFICATION
AUDIO
JUNCTION BOX
TO AIRCRAFT POWER
CONTROL BOX
SWEEP CONTROL
RANGE RELAY
POWER
AUDIO
RADAR RANGE
PHASE REFERENCE
DEMODULATED VIDEO
CLAMP
INDICATOR AMPLIFIER
DEFLECTION VOLTAGES
CLAMP
INDICATOR

FIGURE 2. Block diagram of AN/APG-15B and AN/APX-15 systems.

and measuring the range of the echo. It receives a synchronizing pulse and the output from the receiver from the transmitter-receiver unit, and in turn, supplies *automatic volume control* [AVC] voltage to the transmitter-receiver unit. The outputs of the range unit are: a voltage proportional to the range of the target, reference voltages for measuring range, a voltage which varies when a target is found, and the modulation from the signals being range-tracked. The indicator-amplifier is a separately cased unit whose principal function is to compare the phase of modulation on the signal being tracked with the mechanical phase of rotation of the antenna assembly, to determine the direction and amount of the pointing error. This information, together with the radar range of the target, is assimilated in the indicator-amplifier and converted into suitable voltages for the indicator. The indicator-amplifier also supplies an amplified version of the target echo modulation to the identification unit, where it is examined for frequencies which can arise only from B-29 propellers. The indicator is small enough to be clamped directly to the pedestal sight and the precise angle information and rough range information is presented on a 2-in. cathode-ray tube. The presentation is type G.

Besides being the power and information distribution center, the junction box contains relays whose operation determines the type of range information fed to the computer. Under normal conditions, the computer receives optical range while the radar set is not locked on a target. When the range unit establishes that a target has been found, the relays automatically switch the computer range input from optical to radar. Identification of the target being tracked is indicated by a light mounted in view of the tail gunner. The identification light is turned on automatically if the target being tracked is a B-29; the light does not turn on if the target being tracked is not a B-29.

19.2.2 Antenna Characteristics

The antenna assembly is designed to give reasonably large coverage as well as fairly high angular accuracy. The antenna feed itself is a standard current-fed dipole and disk; the reflector is a 13-in. paraboloid offset 4½ degrees from the axis of the antenna feed and rotated about the antenna feed. The resulting pattern gives an azimuth coverage of approximately 30 degrees and an elevation coverage of approximately 35 degrees. The one-way crossover is at approximately 70 per cent power, resulting in a power sensitivity of approximately ⅓ db per degree. The antenna assembly paraboloid is rotated at a governed speed of 2,150 rpm. This speed is selected so that the fundamental modulation frequency and the second harmonic of the modulation frequency will exactly straddle the band of modulation frequencies expected from a B-29 propeller. In this way the identification unit can identify a B-29 simply by passing the frequency band 2,400 to 3,780 rpm.

19.2.3 Operational Performance

Only one combat wing of B-29 aircraft was equipped with AN/APG-15B. However, the experience of this wing, together with test results obtained in this country,[28] permits a reasonable estimate of the performance of the equipment corresponding to the three basic functions of the system outlined above. The performance is as follows: reliable detection range on fighter, 1,500 yd; angular accuracy within 1,000 yd, approximately ⅓ degree; range accuracy between 1,300 and 300 yd (the range interval acceptable to the computer), 25 yd. During the first three months of combat the equipment was operational on the average 65 to 70 per cent of the time. An analysis of the field report indicates that this low figure came from other causes than engineering design.

Chapter 20

COMBINED OPTICAL AND RADAR FIRE CONTROL

20.1 INTRODUCTION

20.1.1 Advantages of Range-only Systems

In this chapter those fire-control radar systems are discussed which are primarily meant to provide range only; the associated gunlaying systems depend upon optical tracking for directional data. This division of responsibility between radar and the human eye has certain advantages, for although the eye is very insensitive to changes in range, it is highly sensitive to changes in angular position. Radar, on the other hand, measures range accurately with a simple compact system, whereas it requires considerable bulk, especially in the antenna structure, to achieve an angular accuracy even approaching that of the human eye. Thus in the radar-optical systems each component is used to its best advantage.

It is true that ranging to ground targets does require that the radar have directional properties, in order to pick out the desired target signal from a group. The requirements imposed on the directional device are much less severe for this application than for complete gunlaying systems, and greatly simplified techniques have been developed. Such techniques may be adapted to other uses, notably to night-fighter interception and attack (see Section 20.7.3).

20.1.2 The Application of Range-only Systems

The tactical applications of range-only systems can be divided into the following classes.

Air-to-Air

This application includes systems for use by fighter aircraft in attacks on other fighters or bombers, as well as by bombers trying to shoot down attacking fighters. The need for range data is twofold: to inform the gunner when the target has approached near enough for him to start effective fire, and to feed range data into a computing gunsight which will permit introduction of ballistic corrections and deflection shooting.

Radars developed to provide range information for air-to-air firing are called *airborne range only* [ARO] systems. AN/APG-5 is the example to be discussed in this chapter.

Air-to-Sea

This class includes attacks from fighters or fighter-bombers on ship targets. (A similar problem is presented by isolated targets on the ground.) The airplane may use cannon, rockets, machine gun fire, or bombs. The radar again is needed to determine whether or not the target is sufficiently close to make an effective attack possible, and to supply range data to a computing device. The chief function of the latter is to provide the ballistic corrections needed to offset the projectile drop in long-distance attacks. The range data are usually fed continuously into the pilot's optical sight.

In bombing from low altitudes, the range information supplemented by data on altitude and ground speed permits determination of the release point with the aid of a very simple computer.

The AN/APG-13A or *Falcon* system is used primarily against isolated water targets which give strong echoes. It requires an operator to follow the target range presented on a scope. The systems mentioned for use against ground targets can also be used under these conditions, but are not limited to them.

Air-to-Ground

This involves attacks on ground targets by fighters or fighter-bombers, having the same armament as in the previous case. (Ranging on one out of a multitude of ships presents a similar problem.) Here the Falcon set, originally developed for attacks on ships, becomes inoperative because of the multiplicity of targets. However, simple systems using a conical scan have been developed which provide range on a selected target.

Such systems are AN/APG-13B or *Vulture*, which, like Falcon, requires an operator and AN/APG-21, *Terry*, which is automatic.

20.2 THE LIGHTHOUSE TRANSMITTER-RECEIVER [LHTR]

20.2.1 Choice of R-F Unit

The *lighthouse transmitter-receiver* [LHTR] is the basic r-f unit now used in most combined optical-radar fire-control systems. [23, 24, 43, 44, 134, 135] The unit is a compact and light (18 in. long, 10 in. in diameter, 28 lb) r-f head, made possible by the development of the lighthouse tube. It operates at S band and is pressurized for high-altitude work. As large antennas cannot be installed very well in aircraft of the type that would use this equipment, the choice of S band resulted in fairly wide beams, of the order of 30 degrees. In the original applications this did not constitute any disadvantage, because the systems were meant simply to determine range of isolated targets and because acceptable maximum ranges could be obtained with the LHTR unit.

20.2.2 Description of the LHTR Unit

The LHTR unit is a completely self-contained transmitter-receiver. It may be described as a box having four connections, namely, power input, trigger output for indicators, r-f output for connection to the antenna, and video output for connection to the indicator. With the exception of the r-f line all connections enter through the same cable.

The unit contains a self-excited modulator, an r-f transmitter, a *transmit-receive* [TR] switch, a local oscillator and associated plumbing for these, a crystal detector, a receiver strip which includes an i-f amplifier, a second detector and video amplifier, and the necessary power supplies for these parts.

The lighthouse tube is basically a normal triode; but such novel ideas have been used in its construction and in the associated plumbing that operation down to S band became possible. The tube is of the "flat-electrode" type, using plane surfaces for cathode, grid, and anode. Because the spacings have been reduced to very small values, with a corresponding reduction in the transit time, it will operate with good efficiency in this frequency band.

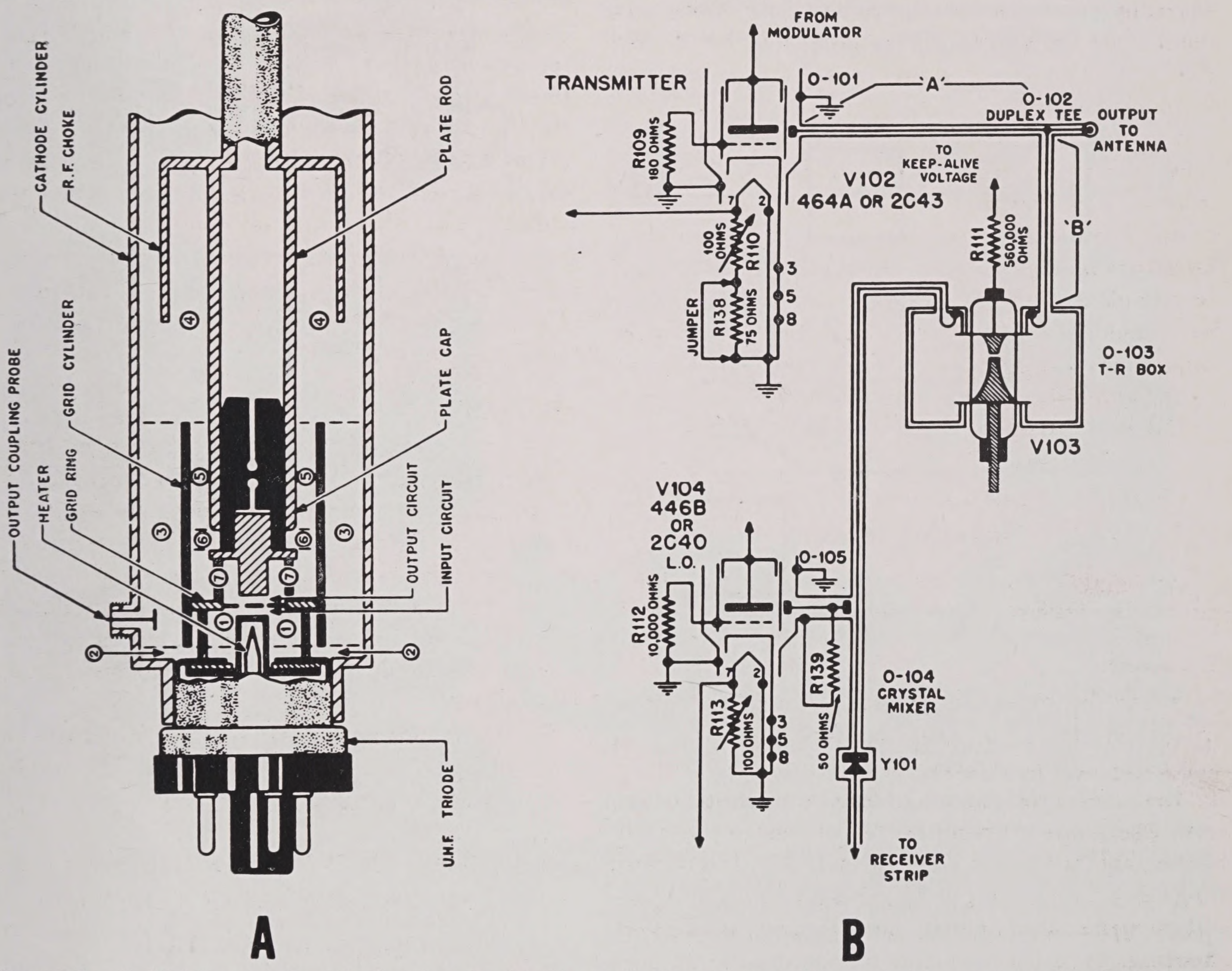

CATHODE CYLINDER
R.F. CHOKE
PLATE ROD
GRID CYLINDER
PLATE CAP
OUTPUT COUPLING PROBE
HEATER
GRID RING
OUTPUT CIRCUIT
INPUT CIRCUIT
U.H.F. TRIODE
①
②
③
④
⑤
⑥
⑦
A
FROM MODULATOR
TRANSMITTER
0-101
'A'
0-102 DUPLEX TEE
OUTPUT TO ANTENNA
R109 180 OHMS
TO KEEP-ALIVE VOLTAGE
V102 464A OR 2C43
100 OHMS R110
R111 560,000 OHMS
'B'
JUMPER R138 75 OHMS
3
5
8
7
2
0-103 T-R BOX
V103
V104 446B OR 2C40 L.O.
0-105
R112 10,000 OHMS
R139
R113 100 OHMS
50 OHMS
0-104 CRYSTAL MIXER
Y101
TO RECEIVER STRIP
B

FIGURE 1. A. Lighthouse tube and r-f cavity. In this figure, ① is the grid coaxial line, ② is the coupling region from the feedback coaxial line ③ to ①; ④ is the coupling region from plate coaxial line ⑤ to ③ ; ⑥ and ⑦ are also part of the plate coaxial line; note that ⑥ changes its axial dimension as the plate rod is moved in and out for tuning. B. LHTR r-f deck assembly.

The tube and cavity are shown in Figure 1.[136] The grid is a mesh stretched across the opening of a flat circular disk to which the glass envelope is sealed on both sides. Anode and cathode are part of, and supported by, cylindrical pieces which act as center conductors for two sections of concentric transmission line shown in the same figure. The outer conductor for these lines is formed by a cylinder which is slipped over the grid disk and supported by it. The cylinder in turn acts as the inner conductor of a transmission line for which the outside wall of the cavity acts as the outer conductor. This latter line feeds back energy from the anode line to the cathode line, and thus provides regeneration. Grid bias is supplied through fingers which make contact with the grid cylinder. Energy is taken from the cavity by means of a probe; its position determines the degree of coupling. The general layout for transmitter and receiver cavities is the same. The transmitter cavity is directly coupled to the r-f output line which in turn connects to the antenna. The local oscillator is coupled into the crystal which is connected to the r-f output via a TR located in a separate cavity. Tuning of the transmitter or local oscillator is accomplished by moving the large diameter plate rod which slips over the plate cap. Both tuning controls are brought out through the pressurized can; the local oscillator tuning can be operated by hand during flight. The r-f layout is shown in Figure 1B.

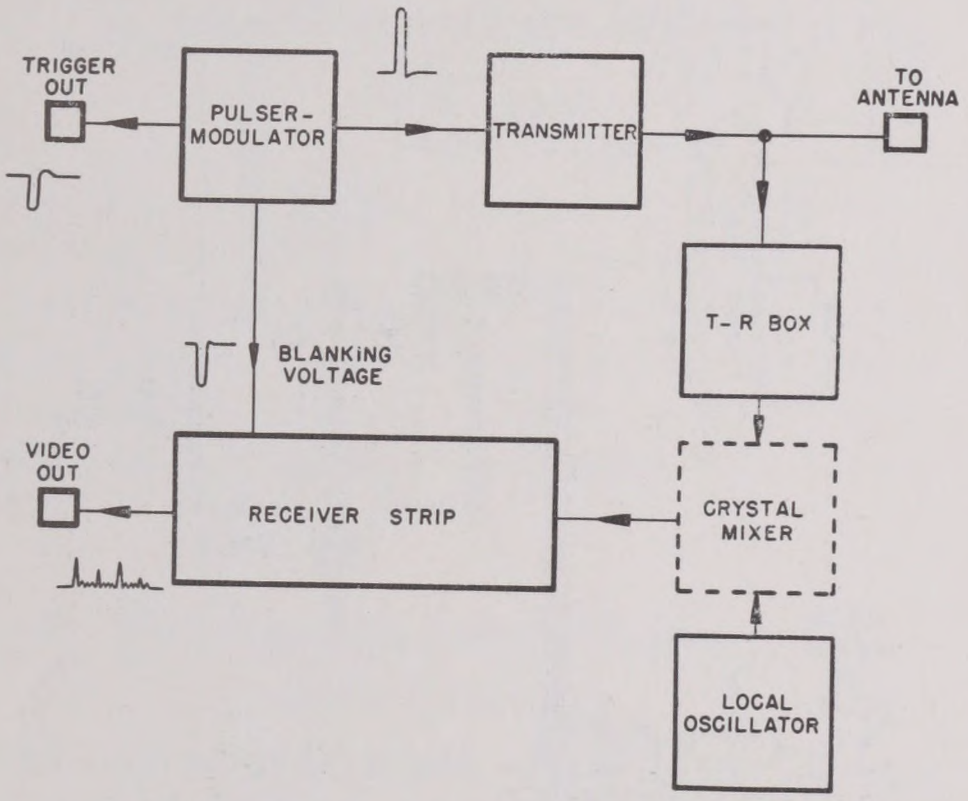


FIGURE 2. Block diagram of LHTR.

The modulator is a conventional self-excited blocking oscillator using a 0.75 μsec delay line. Pulse transformers are used in the blocking oscillator and in the output coupling. The pulse recurrence frequency is approximately 1,200 c.

The received signals are converted in the crystal detector and amplified in the i-f amplifier. The latter is of the triple stagger-tuned type and has a bandwidth of approximately 8 mc. Provision is made for manual or automatic gain control.

A block diagram shown in Figure 2 further illustrates these points. The complete LHTR unit is shown in Figure 3. The total weight of the equipment is approximately 28 lb; its power consumption is 36 watts at 28 v direct current and about 200 watts at 110 v, 400 c alternating current. Its peak power output is about 1.5 kw. The unit has proven itself reliable in operation and has a good degree of frequency stability; in fact manual adjustment of the tuning can, as a rule, be omitted during operation.

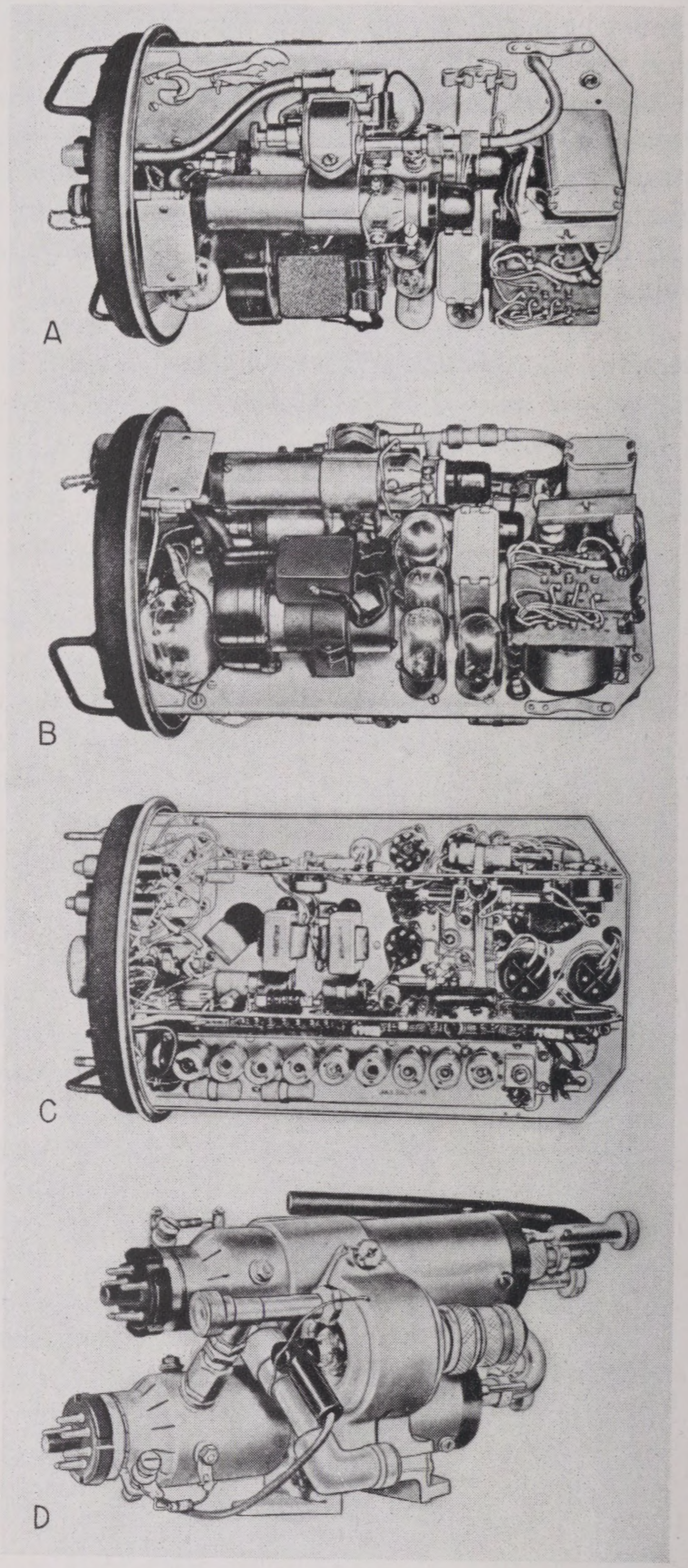


FIGURE 3A. Top view of LHTR.
FIGURE 3B. Side view of LHTR.
FIGURE 3C. Bottom view of LHTR.
FIGURE 3D. Enlarged view of deck of LHTR.

20.3 ARO (AN/APG-5)

20.3.1 Function of the AN/APG-5 System

Airborne range only [ARO] systems[35, 37, 132, 136] were developed to furnish range data to computing sights, as well as to tell the gunner when the target is within firing range. They were intended for gun turrets in bombers, but as the war progressed, more and more attention was given to their use in fighter planes.

The AN/APG-5 system was planned for firing at other airplanes at high altitudes. Under these conditions the number of radar targets is very small and it is sufficient to use a fairly nondirective system in which separation between the targets is made on the basis of range only. In fact, the lack of sharp radar definition is of some advantage, because it permits the system to pick up targets and lock on them even if the antenna is not pointing exactly at the target. This means that the antenna can be pointed along the gun line and need not be offset by the lead angle, as would be required for an antenna with a narrow beam. The large signal obtained from ground return might cause the system to lock on the ground; for safe operation, the system should be used at altitudes which exceed the maximum range of the set. Conversely, this property opens some possibilities of using the set as an absolute altimeter over flat terrain.

Fundamentally, the system uses a set of two consecutive gates which are being swept through the complete range under control of a search circuit. When these gates intercept a signal, they disconnect the searching circuits and lock the timing of the two gates; consequently, the signal will fall partly in the early gate and partly in the late gate. The gate will then stay locked on the target as long as it stays within the range of operation of the set (approximately 200–2,000 yd). The operator can move the tracking away from any undesired target by operating a switch which causes the gates to lock on the next nearer or farther target.

20.3.2 AN/APG-5 System Arrangement and Operation

The system consists of the following parts: antenna, LHTR, range unit, control box, in-out switch, on-target light, junction box, power supply, and cables. Figure 4 shows these parts. The range follow-

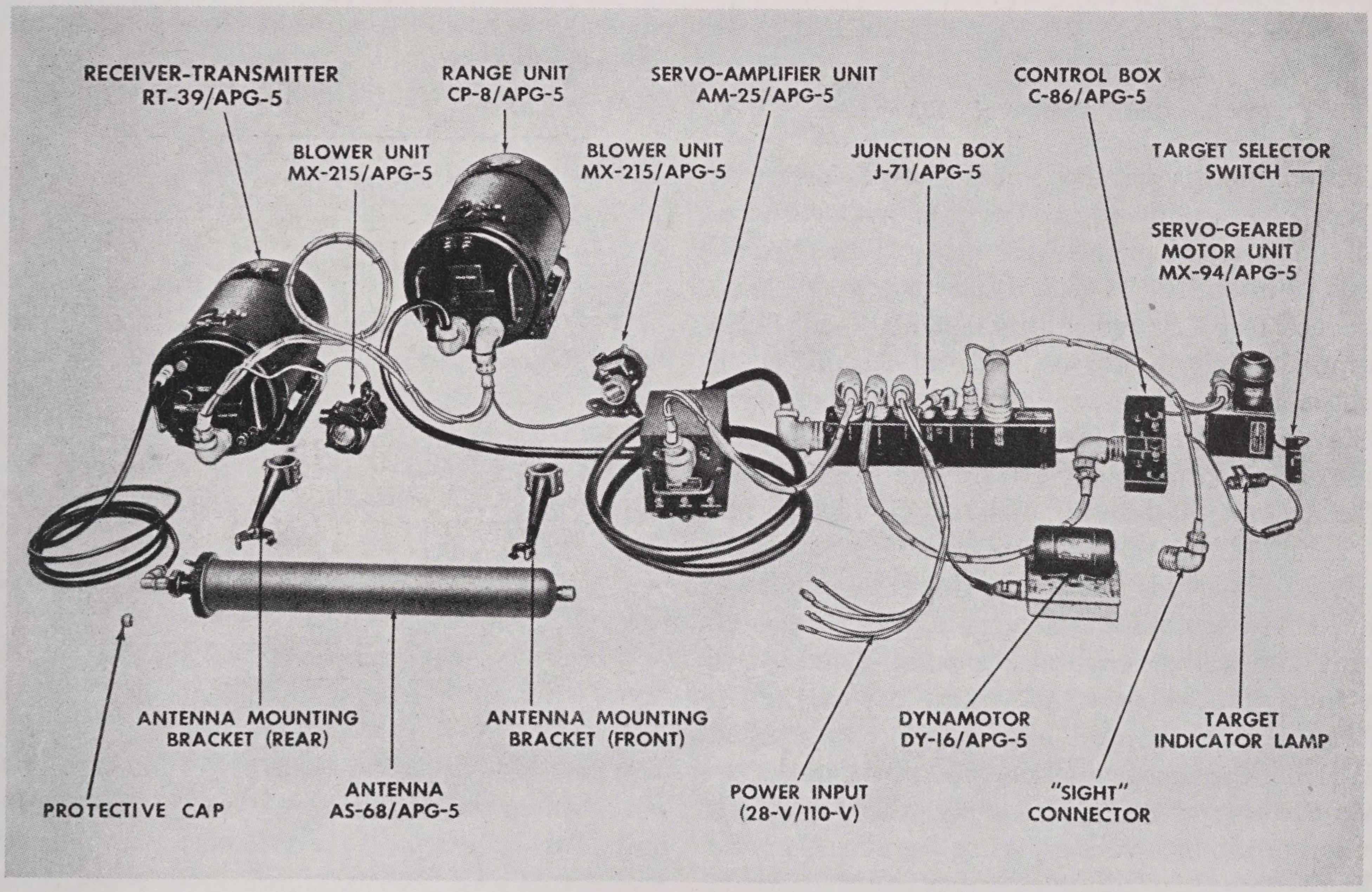

RECEIVER-TRANSMITTER RT-39/APG-5
RANGE UNIT CP-8/APG-5
SERVO-AMPLIFIER UNIT AM-25/APG-5
CONTROL BOX C-86/APG-5
BLOWER UNIT MX-215/APG-5
BLOWER UNIT MX-215/APG-5
JUNCTION BOX J-71/APG-5
TARGET SELECTOR SWITCH
SERVO-GEARED MOTOR UNIT MX-94/APG-5
ANTENNA MOUNTING BRACKET (REAR)
ANTENNA MOUNTING BRACKET (FRONT)
DYNAMOTOR DY-16/APG-5
TARGET INDICATOR LAMP
PROTECTIVE CAP
ANTENNA AS-68/APG-5
POWER INPUT (28-V/110-V)
"SIGHT" CONNECTOR

Figure 4. Components of ARO system.

up unit and gear box are shown, although they are not a part of the radar system. The total weight is 95 lb including power supply. The power consumption is 450 watts at 110 v, 400 c alternating current and 85 watts at 28 v direct current. A block diagram is shown in Figure 5.

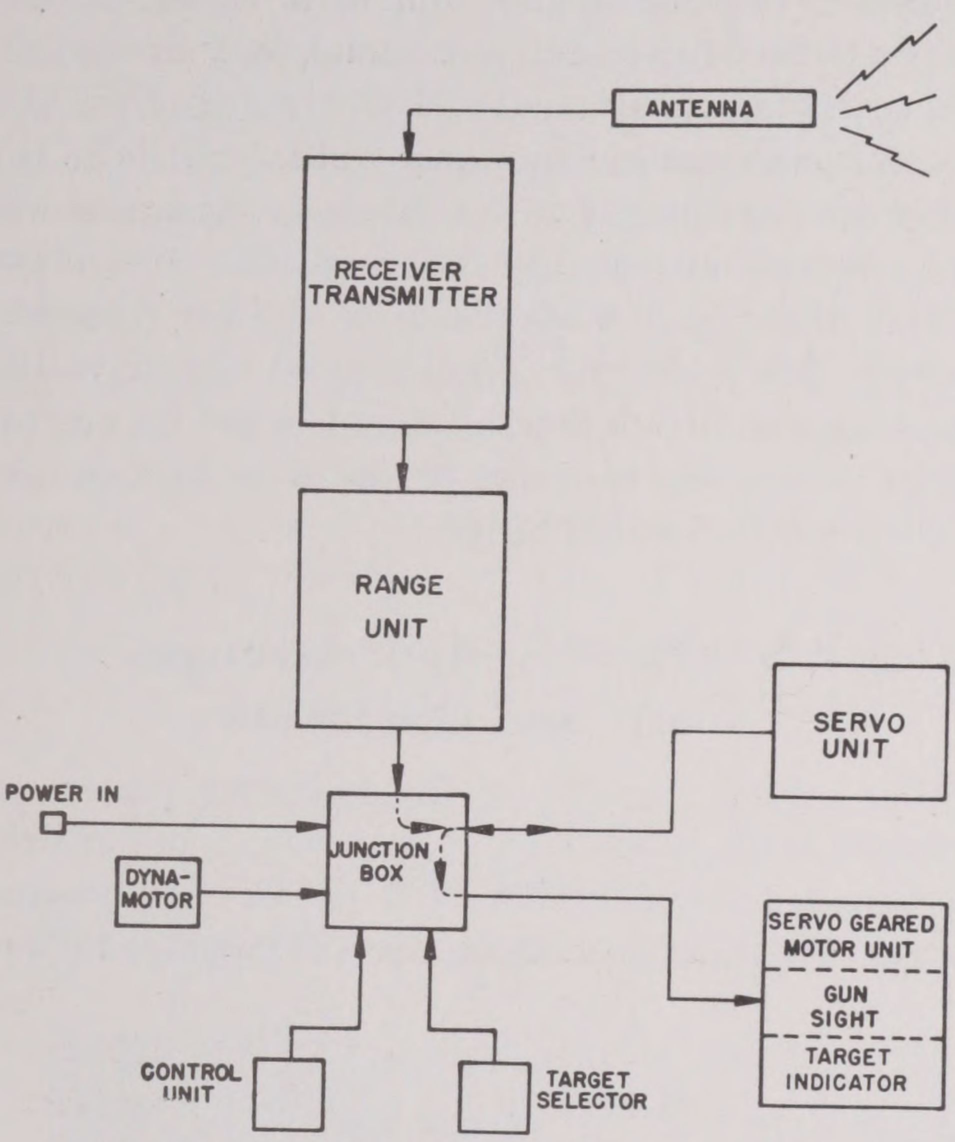

ANTENNA
RECEIVER TRANSMITTER
RANGE UNIT
SERVO UNIT
POWER IN
JUNCTION BOX
DYNA-MOTOR
SERVO GEARED MOTOR UNIT
GUN SIGHT
TARGET INDICATOR
CONTROL UNIT
TARGET SELECTOR

Figure 5. Block diagram of ARO system.

The antenna is an 18-element end-fire array. It consists of a section of coaxial line with a set of dipoles for each element of the array. These are arranged to intensify the field in the forward direction and cancel it in the reverse direction. The beamwidth is approximately 30 degrees. The whole unit is enclosed in a cylindrical, pressurized plastic housing.

The range unit contains the circuits which provide search, tracking, switchover from one to the other, and *automatic volume control* [AVC] for the LHTR. The action of the range circuit can best be understood from the block diagram, shown in Figure 6. The LHTR modulator triggers a delay multivibrator. The trailing edge of the pulse generated in this multivibrator can be moved in and out, under the influence of the grid bias on one of its tubes. Apart from the first few microseconds, the delay between the trigger and this trailing edge is a linear function of the bias voltage. After amplification and differentiation this trailing edge controls the start of the very narrow (0.7 μsec) early gate. Its trailing edge, in turn, controls the start of the equally narrow late gate. These gates are applied to the coincidence tubes. The video signals, after passing through a delay line which absorbs the few microseconds over which the delay multivibrator is nonlinear, are also applied to these coincidence tubes. The coincidence tubes can only conduct when the gate and the video are applied simultaneously.

In the search condition, the bias voltage for the delay multivibrator is derived from a saw-tooth generator which sweeps the gates through the total range of the system. Whenever coincidence is observed between a signal and the gates, a signal is transmitted to the detector circuit and amplified in the d-c amplifier. This operates the disconnect relay and starts the unit tracking. As the search sawtooth has been applied through the range condenser in the integrator unit, the initial range voltage on this condenser is already established, and the only problem left is to keep this voltage locked on the target. This is done by the coincidence tubes. If the voltage on the range condenser is larger than that corresponding to the actual target range, most of the video signal will fall in the early gate. This will operate the discharge tube in the integrator, thereby decreasing the range voltage; the reverse holds if the voltage on the range condenser is smaller than that corresponding to the correct range.

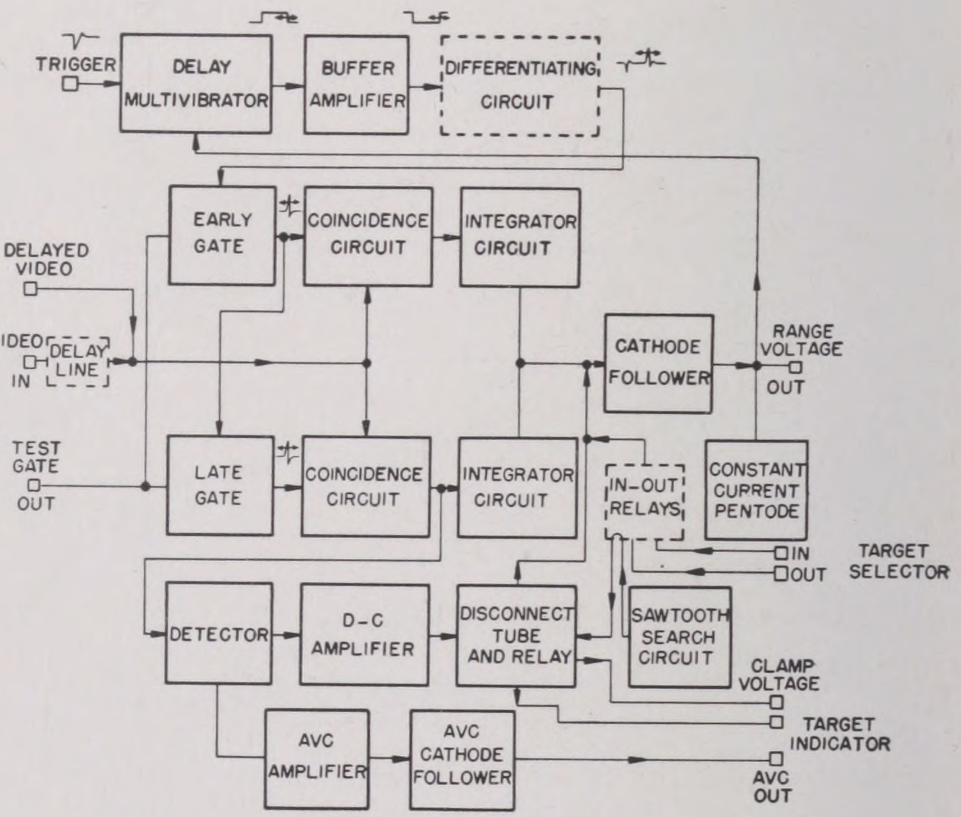

TRIGGER
DELAY MULTIVIBRATOR
BUFFER AMPLIFIER
DIFFERENTIATING CIRCUIT
EARLY GATE
COINCIDENCE CIRCUIT
INTEGRATOR CIRCUIT
DELAYED VIDEO
VIDEO IN
DELAY LINE
CATHODE FOLLOWER
RANGE VOLTAGE OUT
TEST GATE OUT
LATE GATE
COINCIDENCE CIRCUIT
INTEGRATOR CIRCUIT
IN-OUT RELAYS
CONSTANT CURRENT PENTODE
IN
OUT
TARGET SELECTOR
DETECTOR
D-C AMPLIFIER
DISCONNECT TUBE AND RELAY
SAWTOOTH SEARCH CIRCUIT
CLAMP VOLTAGE
TARGET INDICATOR
AVC AMPLIFIER
AVC CATHODE FOLLOWER
AVC OUT

Figure 6. Block diagram of ARO range unit.

When the sight is of a type that cannot accept this range voltage, the latter is delivered to the follow-up unit. This unit contains a differential amplifier system which controls two thyratrons. These provide power to the motor located in the gear box and control it in such a way that it provides a shaft rotation proportional to range, which operates the lead-computing sight.

The control box contains the power switches, fuses, and pilot lights for the 110-v and 28-v lines, as well as a switch which permits manual ranging. The on-target light and the in-out switch are each provided with a long cable to permit installation in the most convenient spot for either gunner or pilot.

20.4 FALCON (AN/APG-13A)

20.4.1 Function of the Falcon System

Falcon [33, 34, 40–42, 120, 122, 123, 126, 131] was originally developed for use with cannon-equipped B-25 airplanes. At an early stage of this work it was found that the destructive range of the cannon (approximately 6,000 yd) far exceeded the range (about 1,500 yd), over which hits could be obtained by point-blank firing. This is caused by the ballistic drop which the projectile suffers in its trajectory. Under these conditions the advantage of the heavy cannon did not appear to justify carrying the extra weight. Yet it seemed fundamentally sound to carry a piece of long-range armament to surprise the enemy, killing his antiaircraft crews or forcing them to take cover, then strafing or bombing in comparative safety. Since a flexible gun mount is impractical in an airplane, it was decided to give the gun a fixed mounting, and to achieve the required superelevation by superelevating the whole airplane by the desired amount. This can be done if the pilot's optical sight is depressed by the angle corresponding to the ballistic deflection. Since airspeed, initial range, and altitude can be held fairly well to prescribed values by the pilot, the range to the target is the parameter which has the major influence on the ballistic correction in this problem. As explained before, the human eye is a poor judge of range, so that radar seems the natural solution.

The set which provides the range data for this problem is Falcon or AN/APG-13A. It uses the LHTR which feeds its video signals into an A scope equipped with a precision sweep. A precision range marking "step" is provided, which the operator can adjust so that it matches the target echo. In this operation of matching the echo, the operator cranks the desired range data into the gunsight (NC-2) where a ballistic cam translates the data into the proper sight-depressions. Little objection was raised to the requirement for an operator in the case of the B-25, which normally carries four or five men. The results with this system have been highly satisfactory, as shown by an Army report.[122] It was possible to obtain 60 per cent hits on a target 100 ft wide and 50 ft high from ranges between 4,500 and 3,500 yd, and 67 per cent hits for ranges between 3,500 and 2,500 yd.

During the operational use of this system it was found that deviations from the airspeed for which the sight cam was designed could not be neglected. Moreover the assumption of constant airspeed during the run does not conform to actual conditions, as the pilot may have difficulty adjusting his throttle during the approach dive. Some corrections can be made by an intelligent use of the slope and zero adjustments which are provided in the indicator sweep. A study of this was made in connection with the Vulture system and is discussed under "Ballistic Cams" in Section 20.5.1.

20.4.2 Falcon System Arrangement and Operation

The general arrangement of the system in the airplane is shown in Figure 7, the components in Figure 8, and the block diagram in Figure 9. The basic r-f unit is again the LHTR. Its r-f output is connected to an end-fire array antenna which transmits and receives the signals. This type of antenna has the advantage of low wind resistance and easy mounting and provides sufficient directivity for the purpose (about 30 degrees).

At the transmission of each r-f pulse, a trigger pulse is sent into the A scope where it triggers a linear sweep. The operator observes the received signal and matches it with a range marker. This range marker has the form of a step in the base line, which the operator brings into coincidence with the signal by turning a hand crank. This matching can be done with great accuracy.

The step voltage is obtained in the following way. A potentiometer is connected to a shaft in the optical sight head which also carries the ballistic cam. This shaft can be turned by means of the hand crank shown in the block diagram and is arranged to have a rotation proportional to range; thus, the voltage on the potentiometer arm will be proportional to range. This voltage is compared with the sweep voltage, and at the time when the sweep voltage reaches equality with it, a step in the base line is initiated. Thus, the

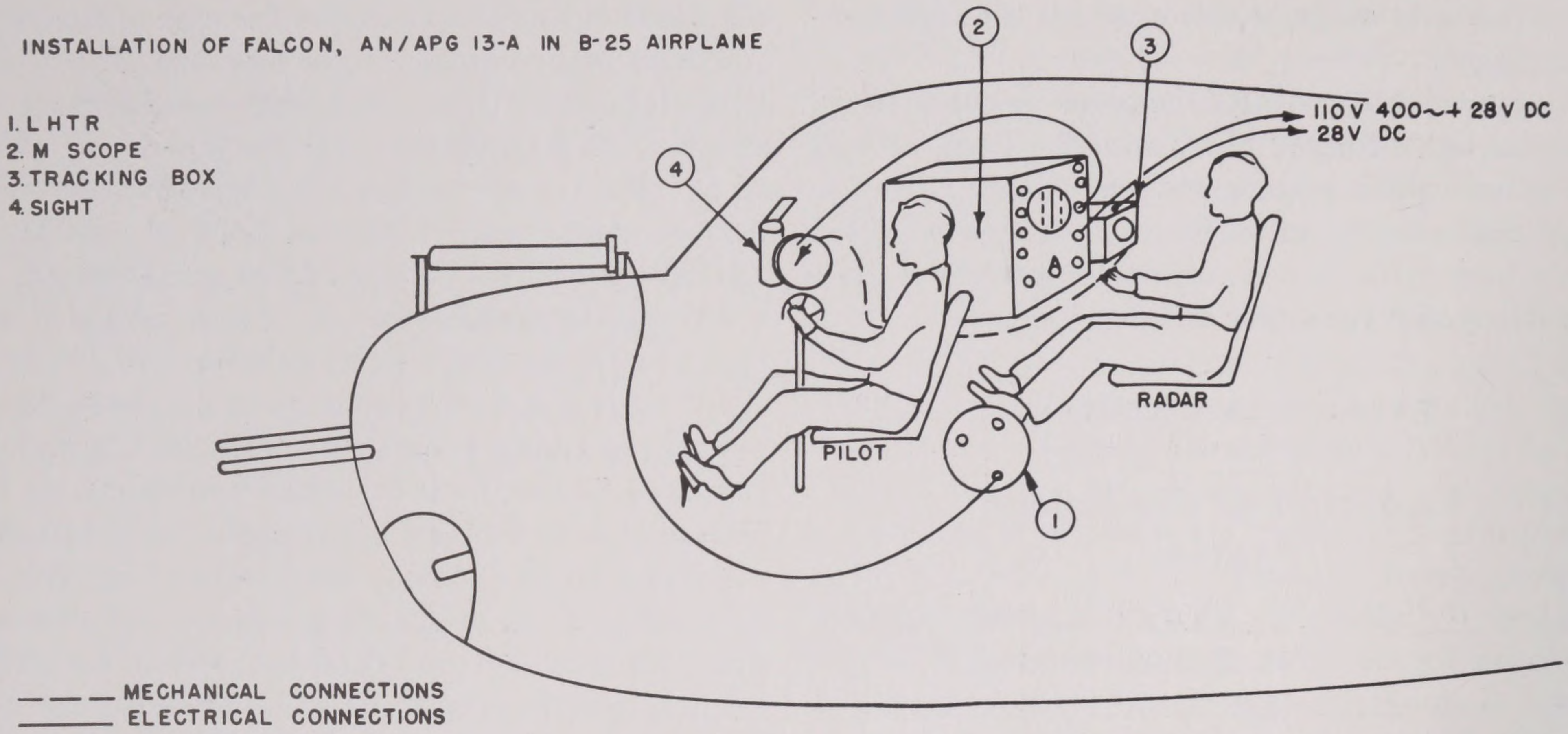

INSTALLATION OF FALCON, AN/APG 13-A IN B-25 AIRPLANE
1. L H T R
2. M SCOPE
3. TRACKING BOX
4. SIGHT
110 V 400~+ 28 V DC
28 V DC
PILOT
RADAR
1
2
3
4
MECHANICAL CONNECTIONS
ELECTRICAL CONNECTIONS

Figure 7. General arrangement of Falcon system in an airplane. The radar components and men are shown disproportionately large.

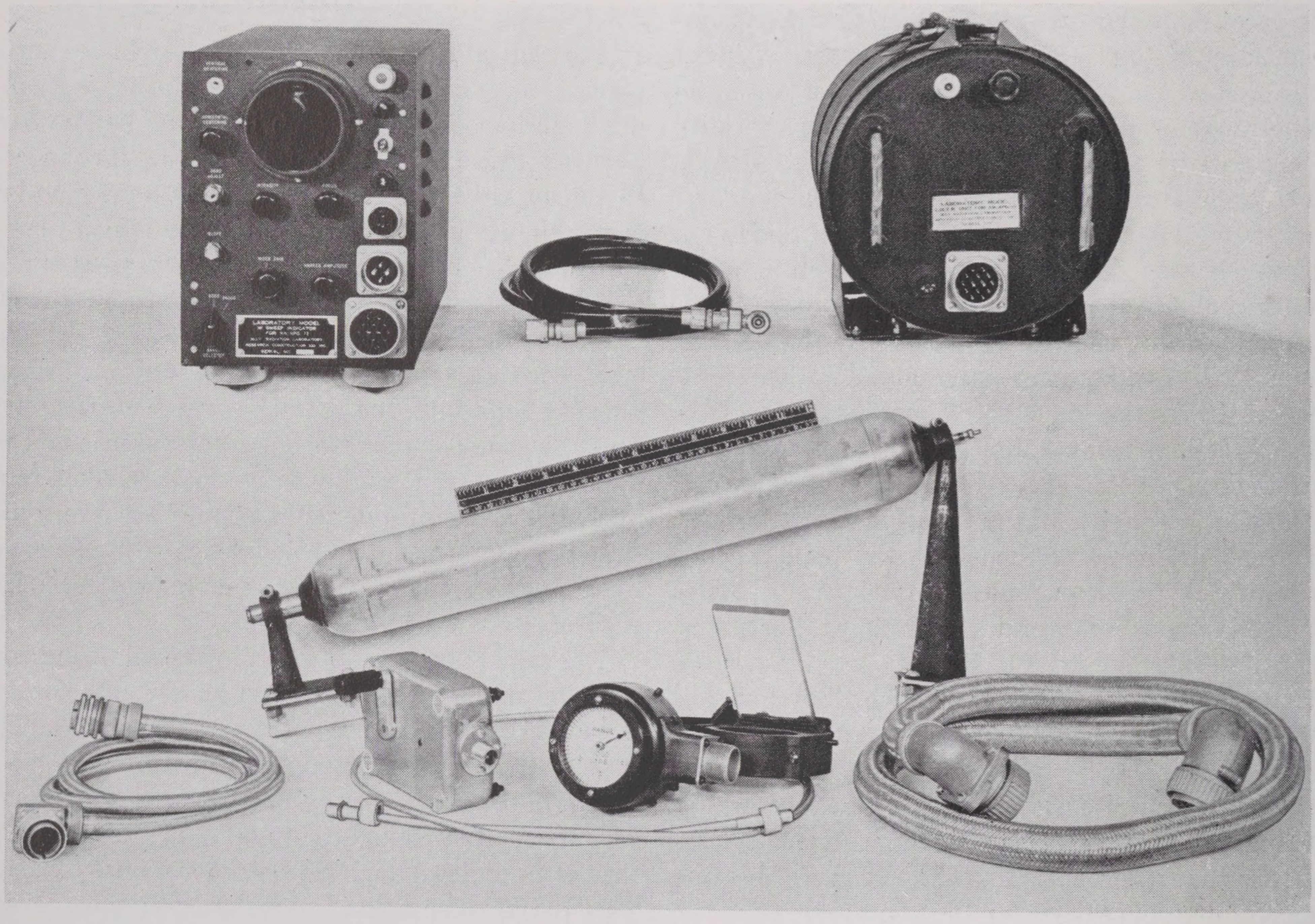


Figure 8. Components of Falcon system.

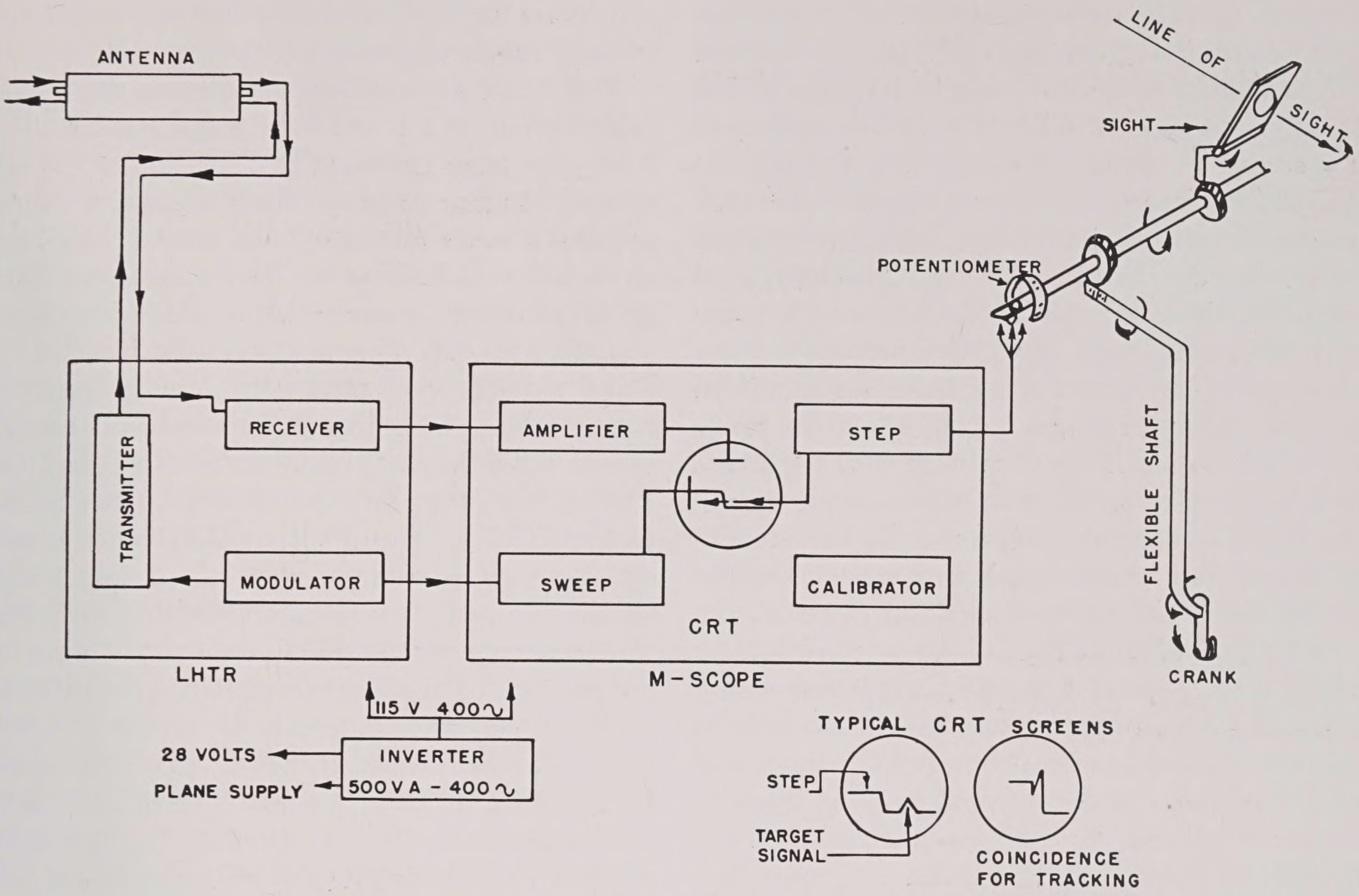


Figure 9. Block diagram of Falcon system.

operator can crank in range by rotating the camshaft until the step and the signal match. By so doing he has automatically cranked the proper ballistic depression into the pilot's sight. As this is a continuous process, the pilot can fire at any time during the run after the radar operator has told him that he is tracking.

Obviously a high degree of linearity is needed in the sweep. The primary parameter used in measuring radar range is time, but if the sweep is truly linear, measurement of a voltage may be substituted for the measurement of time. This is done in the Falcon system by comparing the voltage on the sight potentiometer with that of the sweep. Therefore, if the sweep is nonlinear, erroneous range measurements will result. Considerable work was done on this problem by the indicator group at the Radiation Laboratory and a very nearly linear sweep circuit resulted. Descriptions of these circuits will be found in the Radiation Laboratory Technical Series books on indicators. It will also be clear that the linearity of the sight potentiometer must be as good as that of the sweep, but this is a fairly simple manufacturing problem.

The indicator, a modified A scope with range step, is called an M scope. Apart from the sweep and step circuits, it has the usual video amplifier circuits, provision to mix the video and the step voltages, and to blank the cathode-ray tube beam during the unused time intervals between r-f pulses. A built-in set of range marker pips is provided for calibrating the operation of the range measuring circuits during flight. An additional long-range sweep (24,000 yd) is provided.

The pilot's sight has an optical system which produces a collimated image of a target bead and surrounding ring on a piece of plane-parallel glass, interposed at an angle in the pilot's line of sight. Variation of the angle of this glass plate will change the elevation of the target bead. The glass is mounted on a shaft which is spring-loaded and has an arm resting with a point on the ballistic cam. Thus, rotation of the camshaft will introduce the proper ballistic correction. The relative orientation of the cannon with respect to the reference line of the airplane must be determined with great care, and the optical sight must be carefully harmonized with the cannon. Proper harmonizing charts and procedures for this purpose have been developed.

With the Falcon system the following operations take place during an actual attack. Having checked the correct operation of the set, the radar operator will make sure that the range dial has been cranked to the maximum range. At fairly long ranges (7,000 or 8,000 yd) the pilot will begin to fly his airplane so that the bead of his sight is centered on the selected target, and will inform the radar operator of this fact. As soon as the radar operator has identified the target signal on his scope, he will either wait until this signal moves in (to the left) so as to coincide with the range step at maximum range, at which time he will begin cranking; or if the target signal has already moved below the maximum range, he will crank the range step to the left until it has caught up with the target echo. In either case he will continue to crank at such a rate that the range step moves to the left in coincidence with the target signal, and will inform the pilot that firing can commence. From there on, the pilot can fire as often as the cannoneer can load.

As the closing speed of the airplane is reasonably constant in such an approach, it seemed possible to relieve the radar operator of some of the burden of manual cranking. For this purpose an aided-tracking box was developed. It contains a constant-speed motor and a variable-speed (ball and disk) transmission. The operator sets a knob at the indicated airspeed and releases the mechanism when coincidence of step and echo is obtained. Provision is made to feed in the corrections needed to compensate for acceleration during the approach.

20.5 VULTURE (AN/APG-13B)

20.5.1 Function of the Vulture System

By the time that the Falcon system began to be operationally available, the tactical situation had changed so much that its primary targets, isolated ships, were hardly to be found within the operating ranges of the cannon-equipped airplanes. At the same time the use of cannon fire on land targets became increasingly important and it was desired to employ the B-25's equipped with Falcon for this purpose.

Unfortunately, when Falcon is operated over land, many echoes appear on the indicator and the radar operator cannot easily determine which echo represents the target at which the pilot is pointing his plane. An improved type of radar is therefore needed. It must combine a fairly good directional sensitivity with a method of indicating the particular echo toward which the airplane is being aimed.

Vulture or AN/APG-13B [25, 38, 39, 50] was designed to meet these requirements.

The use of a conical-scan gunlaying radar system (see Section 18.1.2 and Figure 2, Chapter 18) had been previously proposed as a solution to the air-to-ground ranging problem. Such a system, however, requires a range gate, set at the correct range, before an on-target indication can be obtained and thus requires knowing the answer before attacking the problem. In principle there are two solutions. One is to make a range gate that continuously searches in range and only locks the system when both range and directional information give an on-target indication. This is the basis for the system known as *Terry* (AN/APG-21). The other method is to present a simultaneous panoramic view of all target signals within the radar beam, together with a clear indication of whether or not such targets are on the scanning axis of the rotating lobe system. This will indicate which of the many targets is the one at which both pilot and radar antenna are looking. (A linkage must be provided to keep the pilot's sight axis and the scanning axis parallel even though the former is depressed to provide the ballistic corrections.) This second approach is used in the Vulture system; its basis is the V scope presentation described below in Section 20.5.2. The military operation of this system is fundamentally the same as that of Falcon; the pilot aims the airplane at the desired target, the radar operator recognizes this target on the scope and tracks it with a range marker. This tracking operation causes a ballistic cam to depress the pilot's sight by the amount needed for the ballistic correction and another cam to depress the scanner axis by the same amount.

AIDED-TRACKING BOX

In range-tracking with Vulture the operator loses the signal more easily than with Falcon, particularly when the pilot is unable to hold the target in the center of his sight. This will occur when the airplane is not flying smoothly in a straight course.

To overcome this difficulty and to provide smoother tracking than can be obtained with the hand crank, an aided-tracking system was developed. The planned airspeed is set in beforehand; when the operator pushes a button, the range marker moves across the scope at the preset speed. A slewing switch is provided, which enables the operator to bring the range marker quickly into coincidence with the target signal at the beginning of the run. If the operator makes no further adjustment, the range fed to the sight cam may gradually deviate from true range; but since the ballistic corrections approach zero as range decreases, good results can be obtained in this way. However, the operator has a knob at his disposal by which he can make minor adjustments to take care of changes in closing speed during the run. The pilot and the scanner must continue to look at the same target as the sight glass is tipped. Normally this would require a servomechanism to make the scanner axis of rotation follow the depression of the pilot's sight. To obviate the weight and complexity which this would introduce, the tracking box was given sufficient power to drive both the sight and the scanner through flexible cables.

Other System Improvements

Receiver overloading will spoil the type V indication and must therefore be avoided. A time sensitivity control (gain expansion) is installed in the receiver and eliminates the necessity for continuous checking of the gain setting otherwise required to prevent overload.

One of the major problems involved in the use of these systems is that of boresighting the scanner — that is, assuring that the axis of rotation of the scanner is parallel to the line of sight. This was simplified by arranging the scanner mount to permit substitution of new scanners, which are preboresighted electrically. Reharmonizing is then the only operation required in the field.

Ballistic Cams

Extensive work was done on the ballistic cams. The cams in the Falcon system were developed for 250 mph airspeed, which proved to be excessive for the B-25 aircraft. Constant speed during the approach was assumed, which would require juggling of the throttles during the run. Attempts were made in the Falcon system to get better target scores by the use of zero and slope corrections, that is, by changing these parameters in the indicator sweep to correct for the difference between actual conditions and those assumed when calculating the cams. New cams were finally designed which assume the more reasonable cruising speed of 225 mph and constant throttle setting during the approach, a condition preferred by pilots.

Allowance for several other factors, such as variations in initial airspeed, initial range, initial altitude, altitude of target above sea level, and temperature was made. The Applied Mathematics Panel cooperated in the design of a circular slide rule which allows zero and slope correction for conditions different from the standard approach to be set in before the run (see Section 21.2.1). Cams using the AMP data are used in the Vulture systems for both scanner and pilot's sight.[72] Firing tests showed that the same high accuracy could be obtained under nonstandard conditions with the slide rule corrections as was previously obtained under the standard conditions for which the cam had been designed.

Adaptation for Rocket Fire

The original plans assumed the use of the 75-mm cannon. As more progress was made in rocketry, rockets took over a major part of the tactical tasks, even though the cannon was still the answer to some specialized problems, such as long-range high-precision firing (for instance into the entrance of tunnels). Further discussion of the use of Vulture and related systems for rockets is given in Section 21.2.

Performance

The Vulture system was extensively tested by the Army;[124] unofficial information seems to indicate that the results were very satisfactory. Range accuracy is shown in Figures 10, 11, and 12, which give the relation between the range as determined by the radar operator and the range determined by photographic means. It can be seen that the operator noticed deviations and started to put in rate corrections when the deviations became appreciable. In Figure 12, firing tests were being conducted with a target altitude of 4,300 ft above sea level; and the slide rule corrections of −270 yd at 5,000 yd, and −100 yd at 1,000 yd were being used to compensate for the deviation from the standard approach. The circles on the graph ("true radar range") represent the actual range-dial readings with the calibration corrections subtracted out.

Twenty-four "crash program" units had been completed at the end of the war, complete engineering data and a manual were available, and an Army directive had been issued to convert all Falcon systems into Vulture.

20.5.2 Vulture System Arrangement and Operation

The system consists of the following parts: antenna assembly, scanner mount, LHTR, indicator,

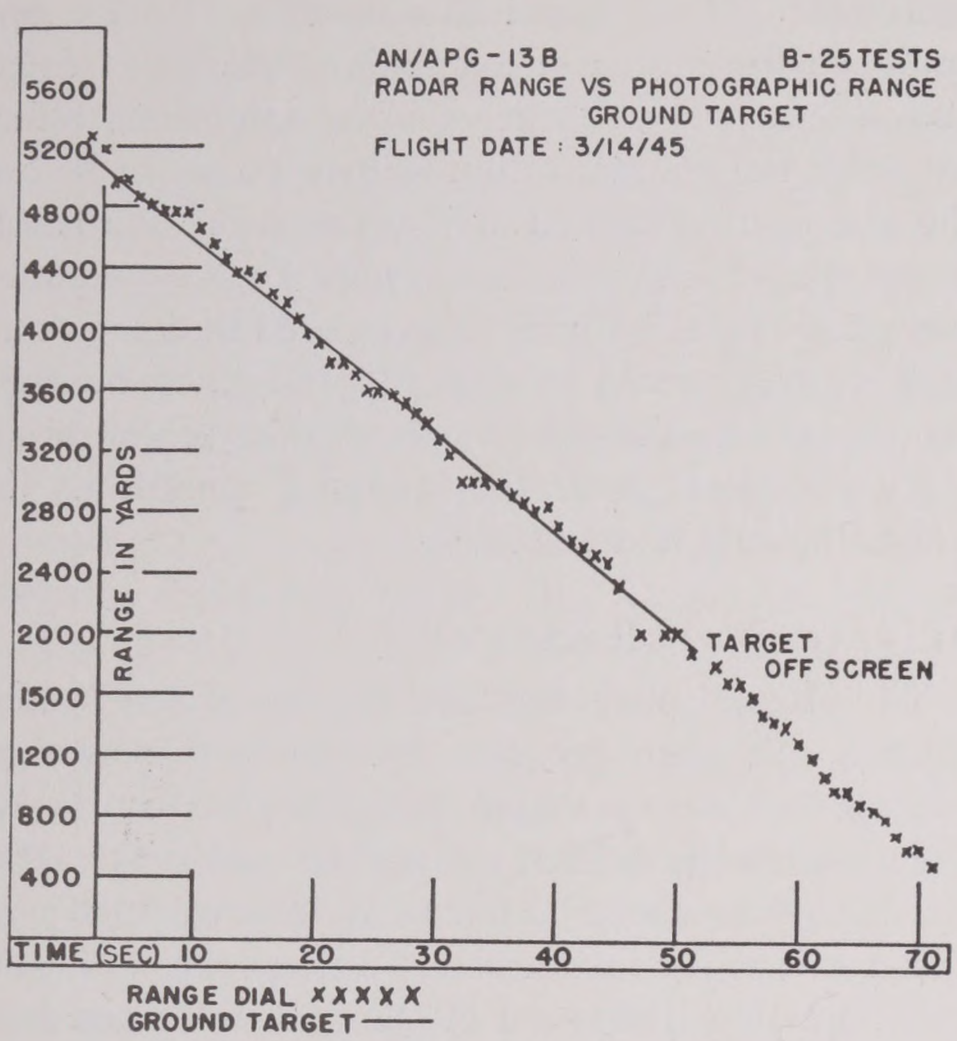


Figure 10. Range accuracy of Vulture system. Radar range is shown by crosses, photographic range by unbroken line.

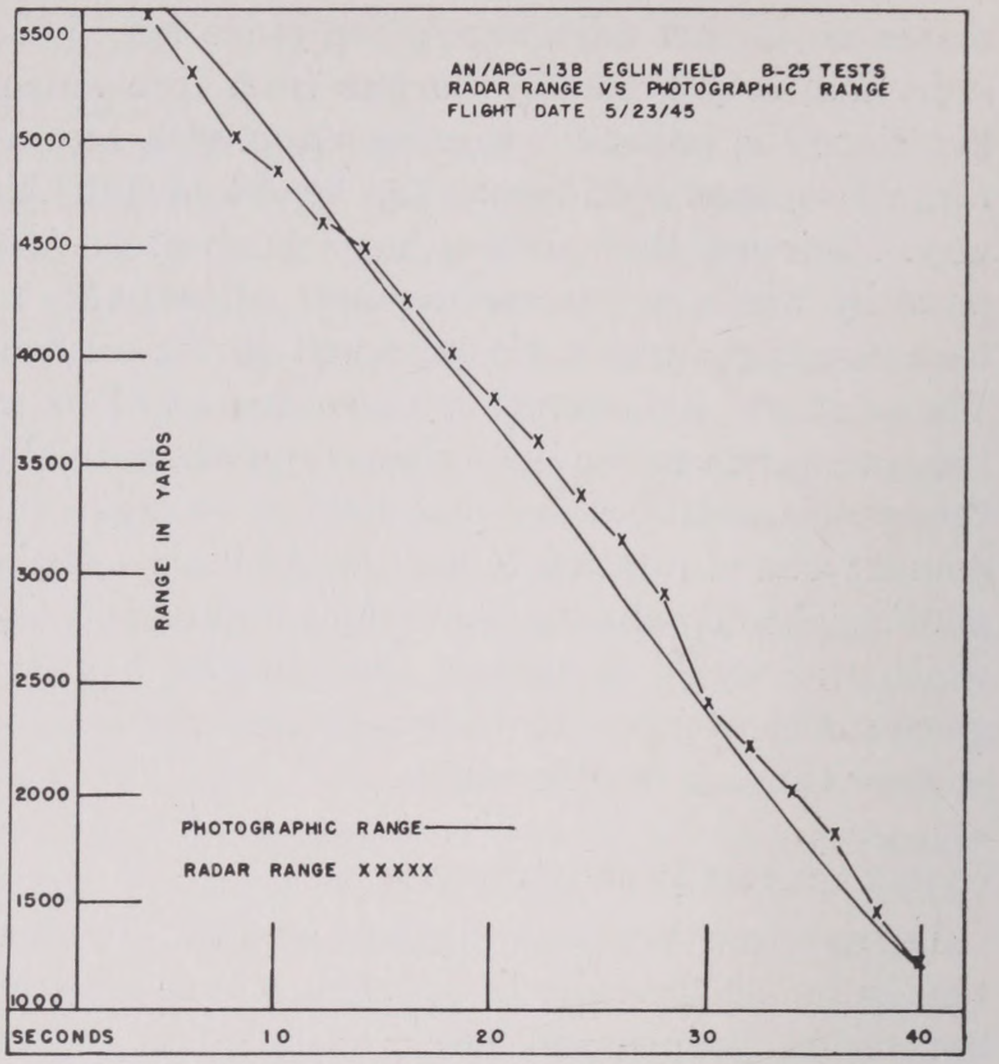


Figure 11. Range accuracy of Vulture system. Test conducted by Army, range accuracy analyzed at Radiation Laboratory.

aided-tracking box, pilot's sight, power supply, electrical and mechanical connection cables. Figure 13 shows some of these. The weight is 135 lb including power supply; the power consumption is 225 watts at 115 v, 400 c and 110 watts at 28 v direct current. Further description of these parts is given below; a block diagram is given in Figure 14, a sketch of the installation in Figure 15.

Antenna

The antenna assembly is the same as that in the AN/APG-15, but the spherical housing and the brackets of the AN/APG-15 are omitted. Instead, the antenna assembly has been equipped with two trunnion bearings. One of these carries the cam-follower bearing and the boresight adapter which is lined up with the scanner boresight axis during the electrical boresighting. The trunnion arrangement makes it easy to change scanners in the field. As the electrical boresighting has been done previously, it is sufficient to insert an optical boresighting tool in the adapter and to reharmonize. The latter is done in elevation by adjusting the zero set on the cam follower and in azimuth by moving the scanner mount.

The scanner mount carries the antenna by means of the trunnions, which in turn allow for movement of the antenna assembly in elevation. A spring pulls the antenna assembly so that its cam-follower bearing is resting on a ballistic cam located in the scanner mount. This cam is driven by the aided-tracking box through a flexible cable which connects to a worm reduction in the scanner mount. The cam is cut in such a way that during the approach the spring tension will help the aided-tracking box. This reduces the load and improves the accuracy. The scanner mount is equipped with a junction box for the cable that brings d-c power to the scanner and also carries the scanner synchronizing impulses.

In the World War II installations of the Vulture system the antenna was housed in a nacelle protruding under the fuselage of the ship. This was done for reasons of expediency; a nose installation would have been preferred if sufficient time to engineer it had been available. The length of r-f and mechanical drive cables was approximately 15 ft.

LHTR

The LHTR is a standard unit. The time sensitivity control (or gain expansion) of the receiver i-f strip is applied through the gain-control lead and does not require modification of the LHTR unit.

Indicator

The indicator is a modified Falcon indicator, equipped to handle either the V presentation or the standard Falcon A scope, at the throw of a switch. In the V presentation, range is still displayed along

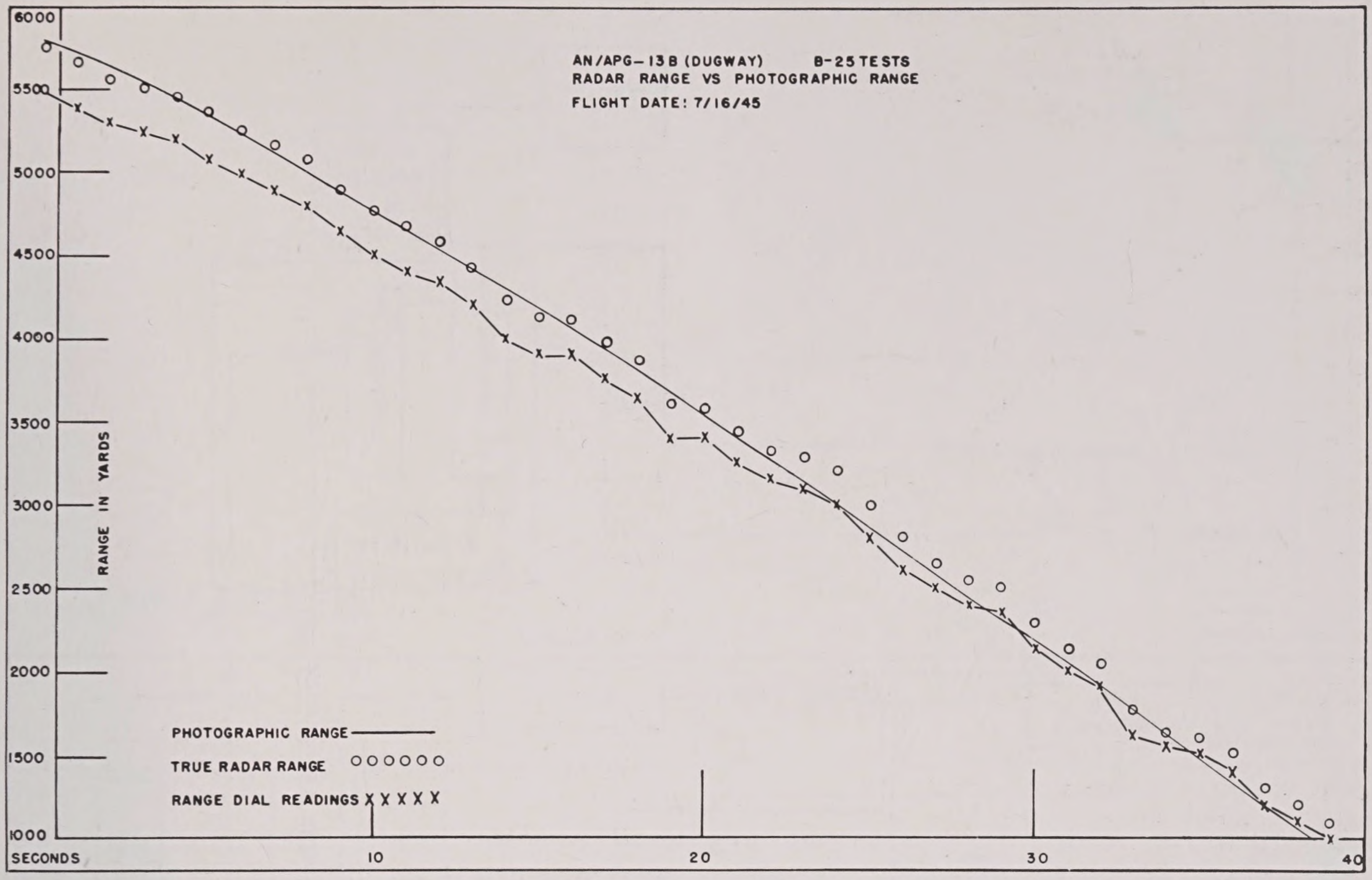


FIGURE 12. Range accuracy of Vulture system, from a firing run in which ballistic calibrations of −270 yd at 5,000 yd and −100 yd at 1,000 yd were used. Tests conducted by Army, range accuracy analyzed by Radiation Laboratory.

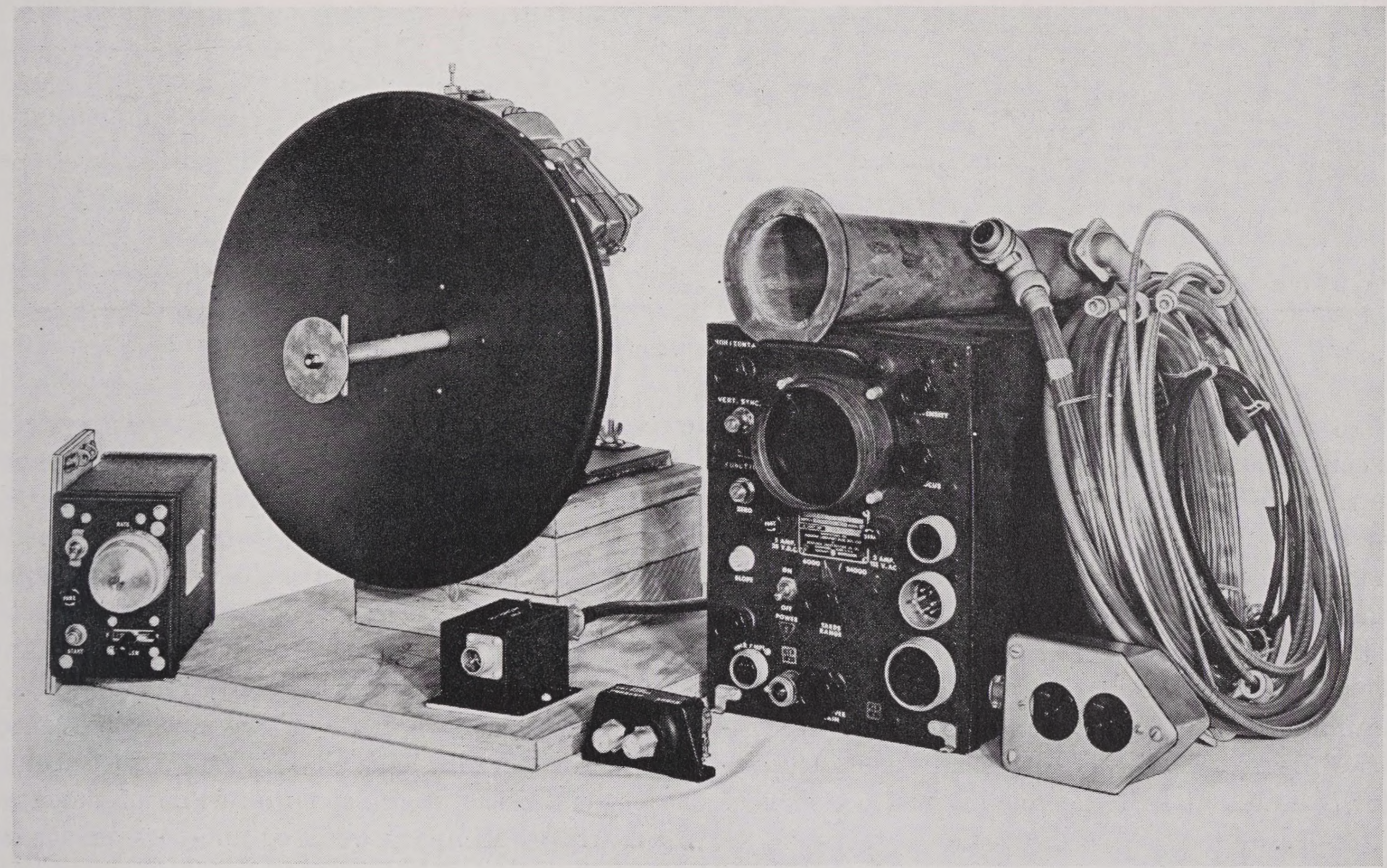


FIGURE 13. Some of the components of the Vulture system. (Aided-tracking box at far left.)

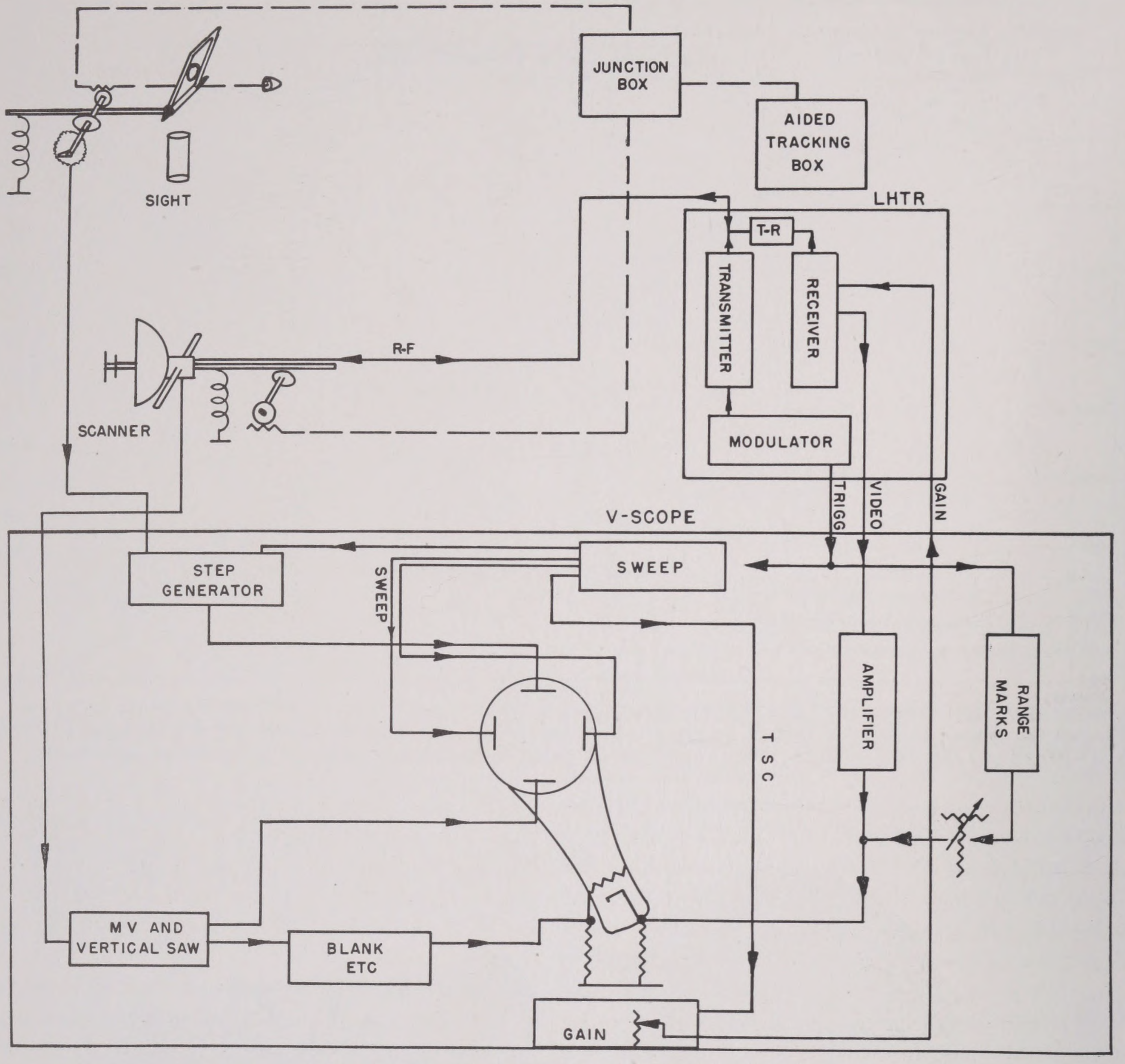

JUNCTION BOX
AIDED TRACKING BOX
SIGHT
LHTR
T-R
TRANSMITTER
RECEIVER
R-F
SCANNER
MODULATOR
TRIGG
VIDEO
GAIN
V-SCOPE
STEP GENERATOR
SWEEP
SWEEP
AMPLIFIER
RANGE MARKS
T S C
MV AND VERTICAL SAW
BLANK ETC
GAIN

FIGURE 14. Block diagram of Vulture system.

the horizontal axis. Two range intervals are provided, 0-6,000 and 0-24,000 yd; the latter does not have a range marker. The video signals have been removed from the vertical plates and applied to the cathode of the cathode-ray tube, resulting in intensity modulation as in a B scope. In the vertical direction the number of degrees of rotation of the scanner is displayed. For the V presentation it was found desirable to display two full revolutions of the scanner (720 degrees), hence the vertical saw-tooth generator operates at half the revolution frequency of the spinner.

For the one target that is on the axis of rotation of the scanner, the average returned signal is independent of the position of the scanner and thus stays constant as the scanner is rotated. For each successive pulse, the beam describes a horizontal trace slightly above the previous ones, and, thus, a target on the scanner axis will produce a series of dots of equal intensity, one above the other, each at the correct range of the target. On the scope this shows up as a vertical line of constant intensity (unmodulated).

For any targets that are off the axis, the average signal intensity will vary as the scanner goes around and thus deposit bright spots on some of the horizontal traces and very weak or no spots on others. On the indicator this shows up as a broken (modulated) line or, in extreme cases, as just two dots. This

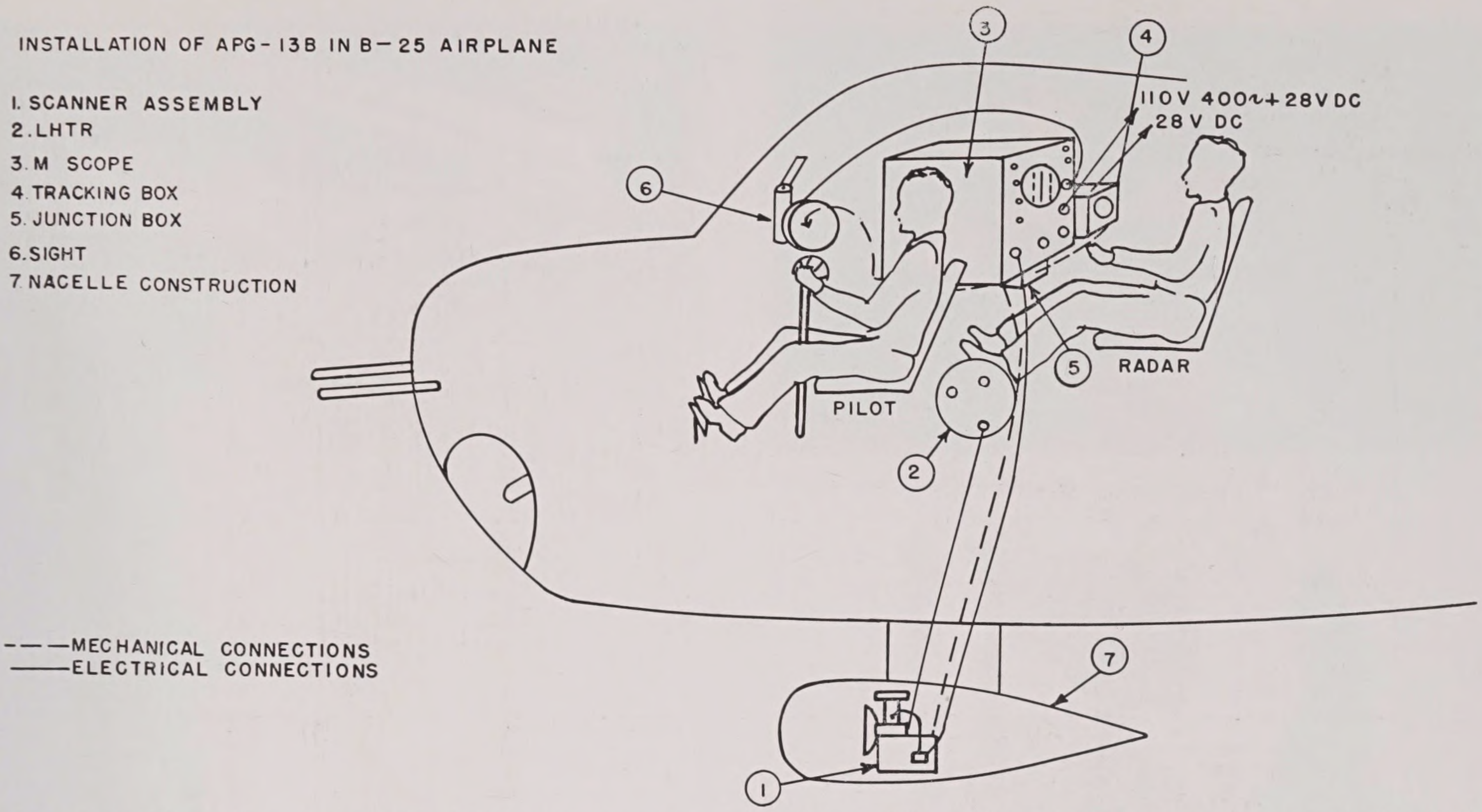


Figure 15. General arrangement of Vulture system in an airplane. The radar components and men are shown disproportionately large.

makes it easy to see which targets are on the axis (that is, which one the pilot is looking at), and which ones are off. The position along the vertical axis at which the target return appears is a direct indication of the position of the target in relation to the airplane. See also Section 20.7.3.

Figure 16 shows some target areas as seen from the nose of the airplane during a typical approach, and the corresponding indications on the V presentation. It can be seen that a large number of confusing undesired targets are present, and these make it generally impossible to recognize the desired target on the A scope. Yet there is no trouble in recognizing the target in the V presentation. These pictures were taken in the early stages of development and neither range marker nor gain expansion had been incorporated in the set. The solid line appearing at the left of the scope presentation is caused by the initial pulse, which thoroughly overloads the receiver.

From these photographs the reason for the choice of two revolutions per scan can also be appreciated. If an off-axis signal is received from such a direction that only the top and bottom part of the presentation show fade-outs, then it would be difficult to judge whether the end of the trace was caused by modulation or because the end of the scanning pattern had been reached. If two revolutions are presented, however, a clear break will always be visible in some part of the trace.

If two targets are present at exactly the same range, one on and one off the scanner axis, then the received signal is the superposition of a modulated and an unmodulated signal, and no clear unmodulated trace appears on the scope. Very often, however, the desired target can be found by looking for the line that has minimum modulation, because any such superposition will not show zero signal at any point of the trace. Such numbers of confusing targets might occur at exactly the same range that recognition would become impossible. Fortunately the tests showed that the number of cases in which the system becomes inoperative is small. These conditions, however, indicate that a sharp beam is a definite advantage for the Vulture system, both for the reason stated above and because the greater concentration of energy will permit ranging on smaller targets. This is discussed in Section 20.7.

The indicator is a modified Falcon indicator, shown in Figure 17, in which two tubes have been added. One tube is a multivibrator which provides the 2 to 1 stepdown from the spinner frequency and simultaneously generates a saw-tooth at this frequency. One half of the other tube acts as a saw-tooth amplifier and the other half provides the necessary intensifying and blanking signals.

The following of the target range is again done by a step in the base line. As the CRT is now operated as a B scope it would be impossible to see any step in the

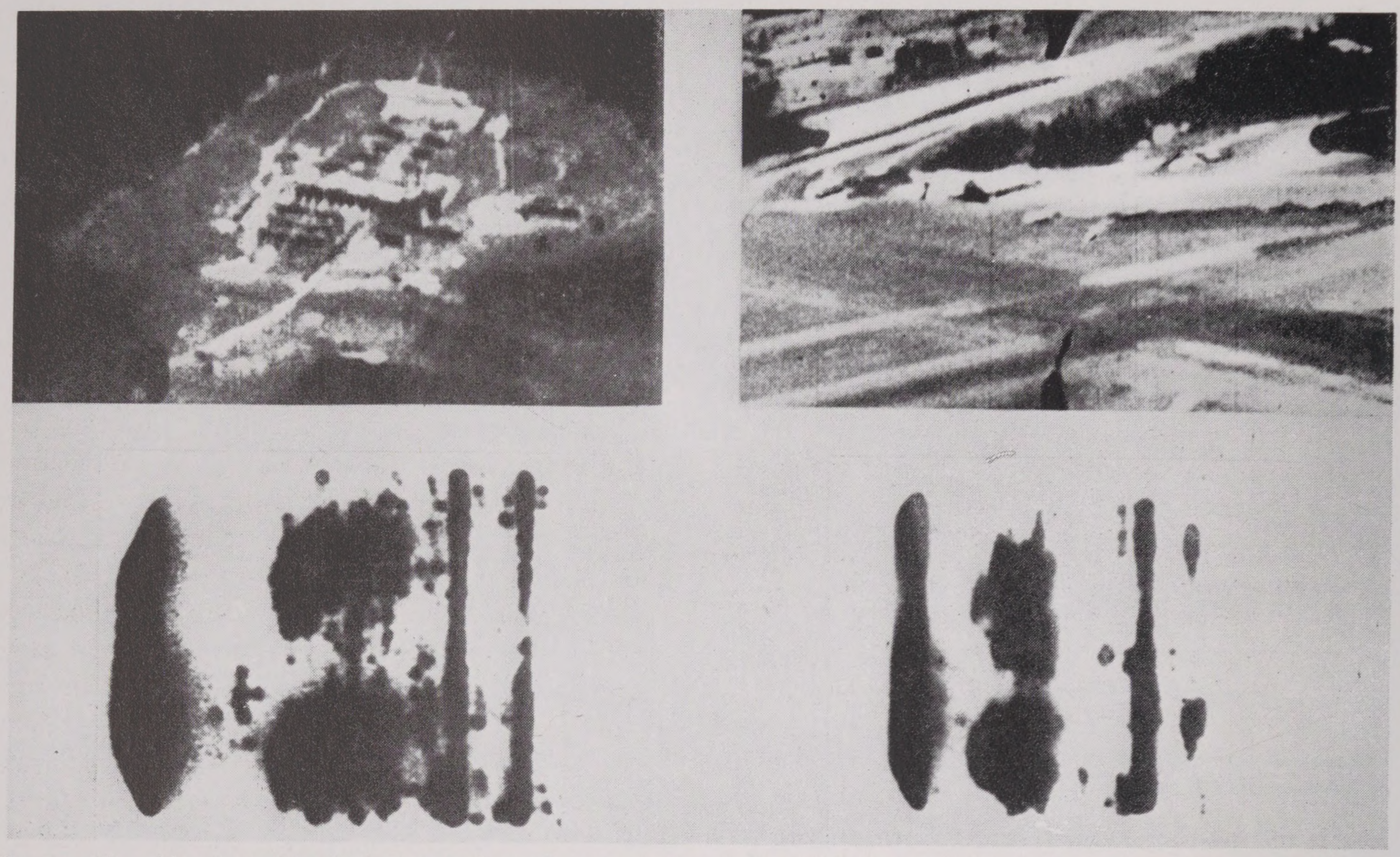


FIGURE 16. Air view of typical targets (transformer station, left, and hangar, right) with corresponding presentation on the V scope. Photographs were made before the gain expansion (time sensitivity control) and range marker were installed. The solid black line at left of scope photographs is caused by the initial pulse. It should be disregarded.

base line because the beam is normally invisible. To overcome this, an intensifying signal is applied at the end of each vertical sweep. This intensifies one or two lines of the scanning pattern at the bottom of the picture. If echoes are received during this period they will cause blooming of the picture and thus make it impossible to see the range marking step, particularly since its amplitude must be kept small. For this reason a paralyzing pulse is applied to the intermediate frequency, which prevents any signal from coming in during this period. Further investigation showed that erroneous on-target indications might be obtained under certain conditions if the amplitude of the step was appreciable. Consequently the step was limited to low values; an attempt to sharpen the step resulted in a small overshoot which was found very helpful in operation.

In this system the eyes of the operator perform a number of the functions requiring circuits in complete gunlaying systems. The human eye is well able to compare brightnesses in different parts of the field of view, remember positions in the field of view, distinguish between stationary and moving impressions, and to integrate. This permits the elimination of balanced detectors, of comparison circuits and indicators, and of integration circuits. Because the data are presented in proper form, it is possible to obtain all the additional functions of the Vulture by the addition of only two tubes to the Falcon indicator.

AIDED TRACKING

The range step is generated, just as in the Falcon system, by comparing the sweep voltage with the range voltage appearing on the range potentiometer in the sight head. The operator is assisted by the high torque aided-tracking box (described in Section 20.5.1), which drives both pilot's sight cam and the scanner cam through flexible cables. It is equipped with a push-button starter and two automatic stops. One will stop the motor when the range has reached its maximum (6,000 yd), and thus prepare the system for a new run. The other stops it at 300 yd. Its purpose is to prevent the tracking box from beginning the reset operation, which would begin to depress the pilot's sight and thus spoil his aim before he has completed his machine gun strafing.

Some minor modifications make this set usable for blind approaches on good radar targets or beacons. They involve turning the indicator tube by 90 degrees and changing the multivibrator speed-control resistance to obtain a 1-to-1 synchronizing ratio. Together with the development of the Terry system, this makes possible a set which would give search, fire control, and AI (Section 20.7).

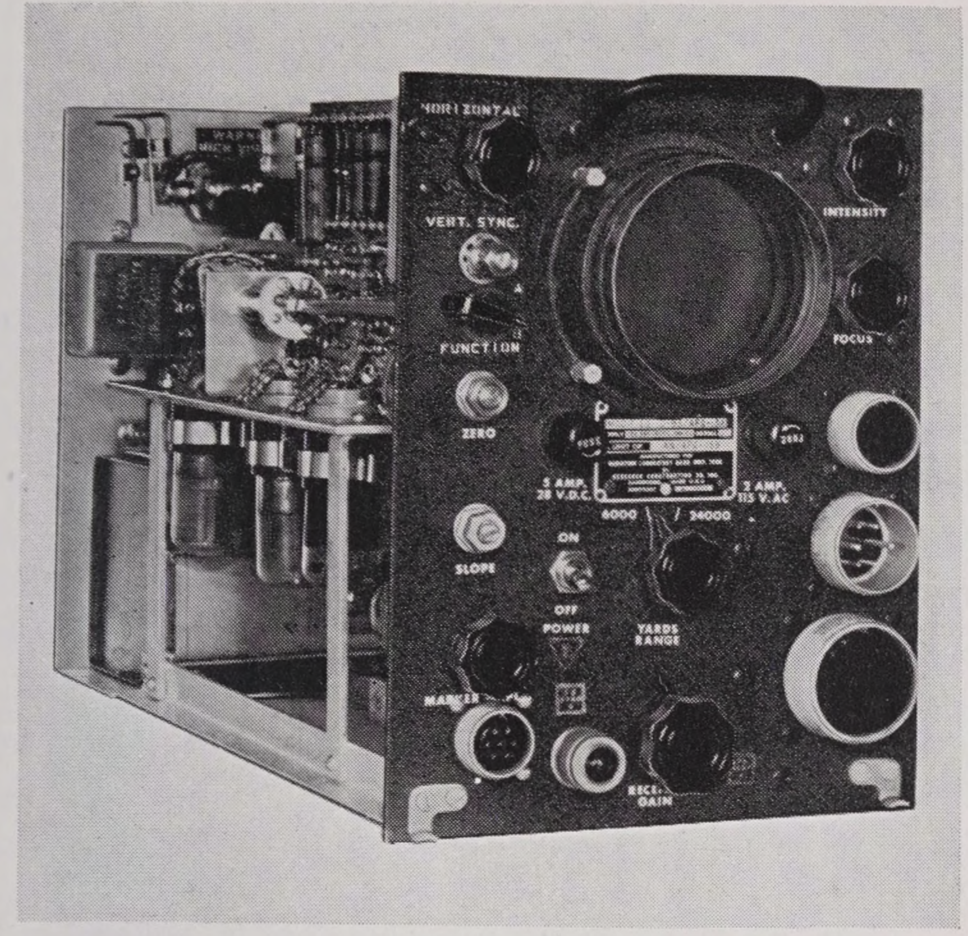


FIGURE 17. Vulture indicator.

20.6 TERRY (AN/APG-21)

20.6.1 Function of the Terry (Automatic Vulture) System

This system was developed for single-seater airplanes where a separate radar operator cannot be carried. Originally this type of airplane was equipped with machine guns only; early radar plans called only for ARO systems, used for air-to-air firing over short ranges and on isolated targets.

As the development of rockets progressed and they became usable over longer distances (see Sections 21.2.2 and 21.2.3) it became more and more important to install them on fighter planes and use them against ground targets. The use of longer ranges brought the same problems of correction of ballistic drop as encountered in the airborne cannon, plus some new ones peculiar to rockets. In any case, it was necessary to have proper range data to feed into computing devices. Except when steep dive angles are used, the determination of the correct range is again a serious problem, a solution for which was sought in the use of radar. If the pilot is to be free from all distracting activities during the actual approach to his target, this radar should be entirely automatic. The Terry system[26, 52] meets the requirements for such a radar system. Theoretical considerations led to an expected accuracy of ±100 yd at 5,000 yd, although this had not been confirmed by actual tests.

The two fundamental methods of obtaining range to a land target from a conical-scan system were discussed under the Vulture system (Section 20.5). The Terry system uses the method of searching through the complete range and of locking on a signal only when both the range and angular information give an on-target indication.

As was mentioned, the system searches through the full usable target range. When a target is located, the range gate tries to lock on the target and then passes the problem on to the modulation tracking circuits. If the target is the one at which the pilot's sight and the rotation axis of the offset scanner are pointing, then the signal will have constant intensity as the scanner goes around. In this case the modulation tracking circuits will exercise no control at all and permit the range gate to stay locked on the target. If the target is not the one at which the pilot is looking, then there will be modulation. The polarity of this modulation will indicate whether the target is closer in or farther out than the one at which the pilot looks. The modulation tracking circuits will then develop a voltage which upsets the range gate tracking and drives the gates in or out as required. This process continues until the correct target has been found, after which the range gates will follow it in. Complete ARO functions are present in this system and the equipment is accordingly built with a switch so that either ARO or Terry operation can be used.

The equipment is particularly adapted to furnish range data to a computing sight, such as the Draper-Davis (Army A-1) sight, or the Navy *pilot's universal sighting system* [PUSS] under development at Franklin Institute.

The pilot's sight and the scanner rotation axis must again point in the same direction, and, thus, the output of the computing mechanism should drive the sight and the scanner in synchronism. The pilot has only to point his airplane at the target by means of his sight and wait until the on-target indicator lights up. After that, he can fire at any time during the approach.

At the conclusion of World War II some experimental models of this system had been built and test-flown. Official tests by Army or Navy had not been made at that time. A set of pictures taken from the nose of the airplane during a typical run is shown together with the range dial indications in Figure 18.

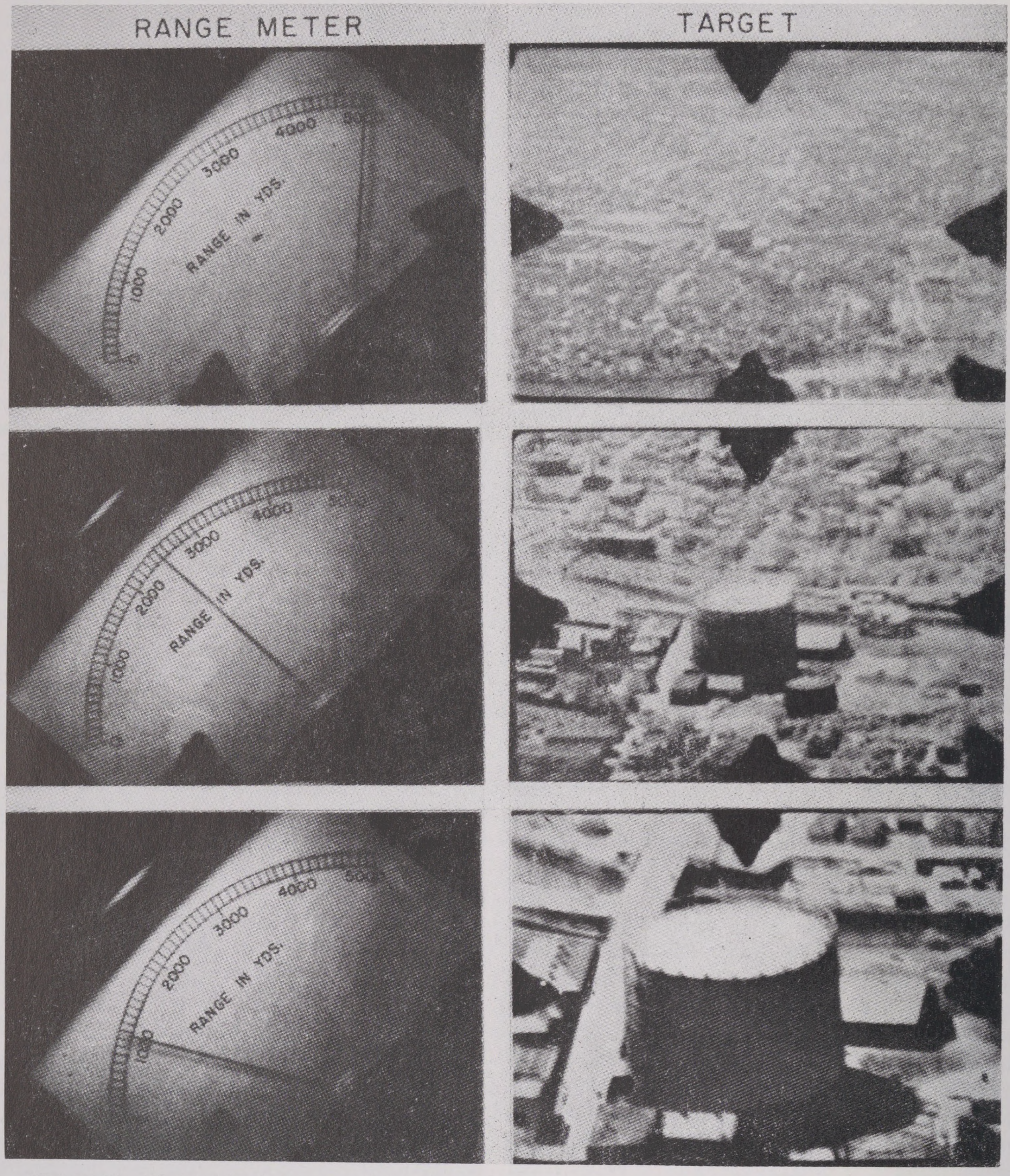

RANGE METER
TARGET
RANGE IN YDS.
1000
2000
3000
4000
5000

Figure 18. Photograph of a target with corresponding range-meter readings taken during a run with Terry.

Six units of this type had been ordered by the Army and the Navy and these units were under construction at the time the war ended.

20.6.2 Terry System Arrangement and Operation

The system consists of the following parts: antenna assembly, scanner mount, LHTR, ARO range unit (modified), modulation-tracking box, pilot's control box, pilot's sight, power supply, cables, computer (may be part of the sight), and servo drive for antenna. The last two items are not considered to be part of the radar system. A block diagram of the unit, exclusive of antenna, LHTR, and computer, is shown in Figure 19.

The antenna assembly is the same as that used in the Vulture system except that the offset of the dish has been increased from 4.5 to 7 degrees, in order to increase the angular sensitivity.

The design of a scanner mount will depend upon the particular computer and sight adopted. If the lead-angle problem is eliminated and corrections are made for ballistic drop only, it is sufficient to drive the scanner in elevation. In this case the scanner mount of the Vulture system is used.

If Terry is to be incorporated into a sighting system which does more than merely compensate for ballistic drop, then the single ballistic cam is inadequate, and is replaced by a computer of some complexity. Cams may still be used in the sighting head and scanner mount, perhaps with a rise which is a linear function of range, to introduce deflection. With such a system a servo drive would be required. With a lead-computing sight like the A-1, the scanner mount must follow the pilot's sight both in azimuth and elevation. An experimental unit of this type was developed under an Army contract at the Massachusetts Institute of Technology [MIT]. In this a fixed sight and scanner mount were used, as all runs were made for photographic recording and none for firing.

The range unit is modified by having leads brought out which make it possible to insert biases in the 6AC7 early and late gate coincidence tubes and from the detector tube located in the range unit.

The modulation-tracking unit is completely new. It detects any modulation that may be present in a signal on which the range gates try to lock and determines its polarity. Referring to Figure 20, let us assume that the range gates in the range unit have locked on target *B*, while the pilot's sight and the scanner are pointing at target *A*. The modulation-tracking box will then detect more signal return when the scanner is pointing up than when it is pointing down. This will set up two bias voltages which are applied separately to the 6AC7 coincidence tubes in the range unit. These biases are of such values and polarities that one will cut off the late gate tube and the other will hold the early gate tube on, so that only the early gate tube acts on the range-tracking circuits. This will move the gate away from the range of target *B* and drive it in

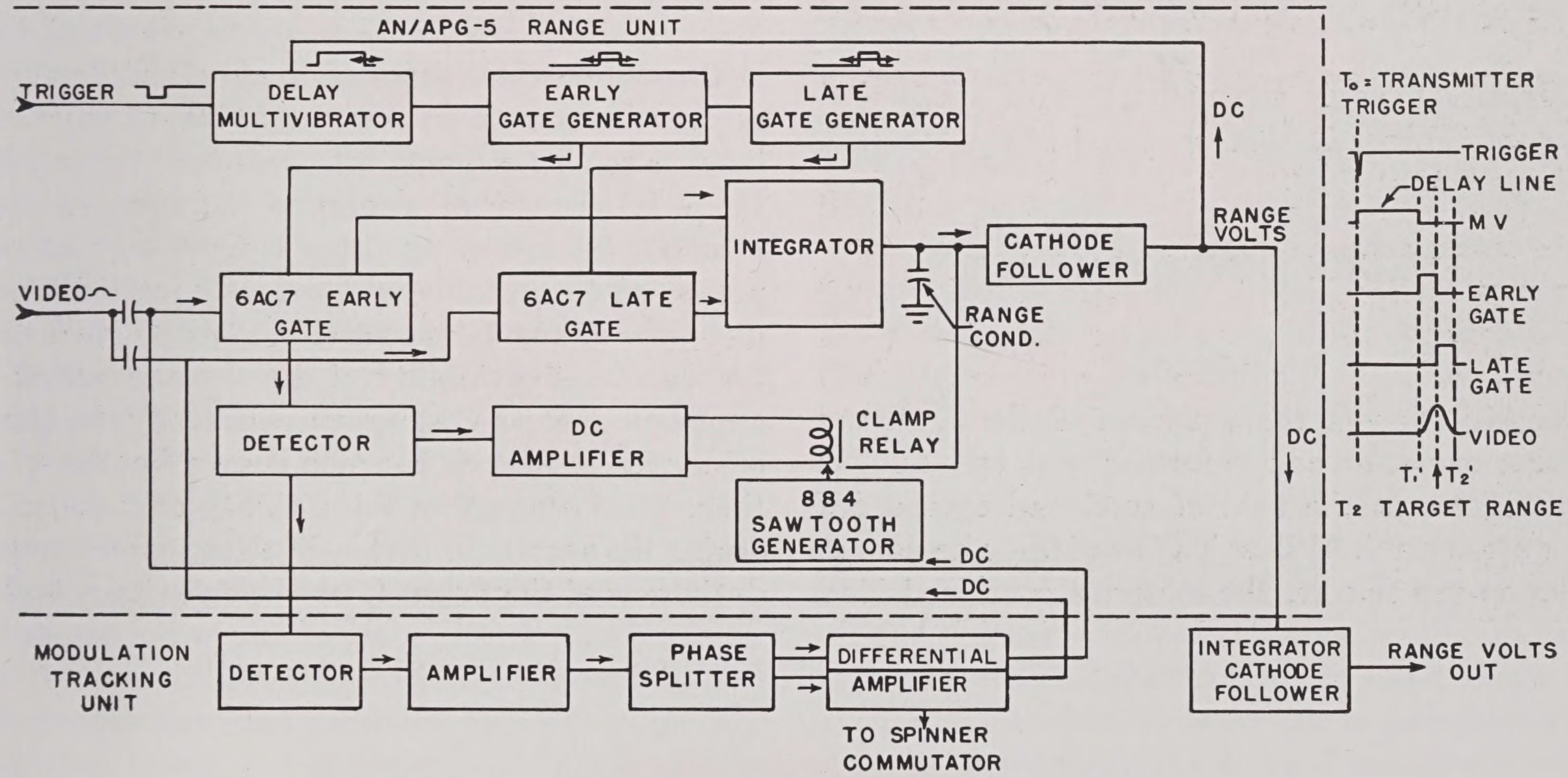

AN/APG-5 RANGE UNIT
TRIGGER
DELAY MULTIVIBRATOR
EARLY GATE GENERATOR
LATE GATE GENERATOR
DC
INTEGRATOR
CATHODE FOLLOWER
RANGE VOLTS
VIDEO
6AC7 EARLY GATE
6AC7 LATE GATE
RANGE COND.
DETECTOR
DC AMPLIFIER
CLAMP RELAY
884 SAWTOOTH GENERATOR
DC
DC
DC
MODULATION TRACKING UNIT
DETECTOR
AMPLIFIER
PHASE SPLITTER
DIFFERENTIAL AMPLIFIER
TO SPINNER COMMUTATOR
INTEGRATOR CATHODE FOLLOWER
RANGE VOLTS OUT
T₀ = TRANSMITTER TRIGGER
TRIGGER
DELAY LINE
M V
EARLY GATE
LATE GATE
VIDEO
T₁' T₂'
T₂ TARGET RANGE

FIGURE 19. Block diagram of Terry search and tracking units.

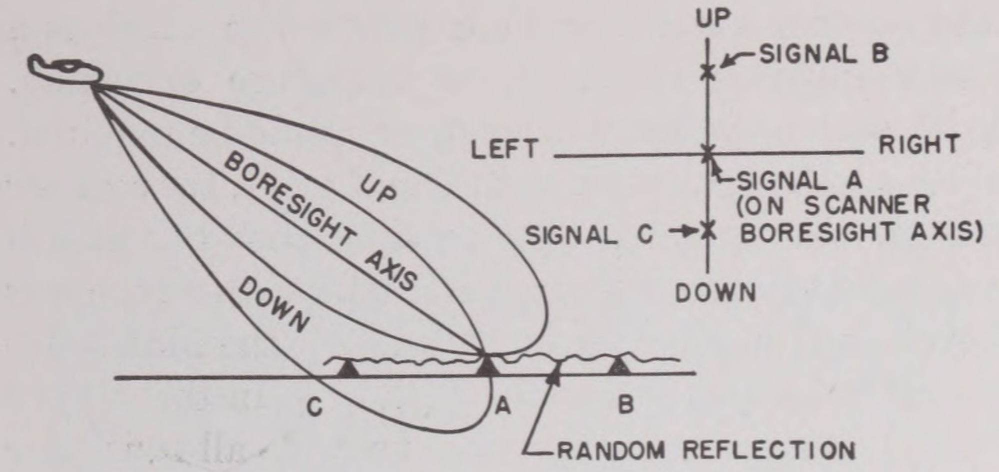


FIGURE 20. Terry antenna pattern.

towards target *A*. The reverse would happen if the gates had locked on target *C*; they would then have been driven out towards *A*. Thus, the modulation-tracking box will drive the gates away, and in the proper direction, from any target for which the signals in the up and down position of the scanner are unequal, and finally leave the gates on the target for which these signals are alike.

The pilot's control box contains a selector switch which switches the set on and off and selects between ARO and Terry operation. Furthermore, it has the pushbuttons as used in the ARO as well as a power-on pilot light and an on-target light.

An installation problem peculiar to the Terry system, which would usually be installed in single-seater, single-engine airplanes, is that one of the desirable locations for the antenna is under the fuselage. Here, however, the propeller may intercept part of the beam. The degree of modulation which would result from such a location and its influence on the tracking must still be determined.

The development of the Terry system together with that of the Vulture opened some interesting possibilities towards the realization of a universal radar set. This is further discussed in the following section.

20.7 FUTURE DEVELOPMENTS

20.7.1 General

The cessation of the activities of the Radiation Laboratory put an end to further work on a number of new ideas in the field of combined optical and radar fire control. Although a few of these items were of a stop-gap nature, the majority contained ideas which definitely merit further investigation and development. Some of the ideas involve further analysis of the operation of the system in order to improve its performance, some involve combinations of techniques now known into a new system, and some involve radically new systems or components. They will be discussed in this order.

20.7.2 Analysis

An important job of investigation remains to be done in the overland systems using conical-scanning methods. This is the determination of optimum values for the r-f frequency, beamwidth, crossover, and time constants.

The present choice of r-f frequency was dictated by the large-scale availability of the S band LHTR unit. The experience gained has already indicated that a narrower beam is desirable, while the antenna size should, if anything, be reduced. Thus the frequency should at least be increased to X band; the possible desirability of K band should be investigated.

Too great a beamwidth causes the r-f energy to be spread out over too large an area and this causes reflections from undesired targets as well as a decrease in the energy falling on the desired target. This latter effect puts a lower limit on the size of the target that can still be satisfactorily detected. Too small a beamwidth causes the beam to be off the correct target over excessive periods because of the pitch and yaw of the airplane, and thus spoils the operation. This shows that the problem is definitely tied in with the stability of the airplane during the approach, as it is not worth while to use beams narrower than the average value of the airplane deviations.

The next problem is the choice of crossover for the beam. For a given beam there still is considerable leeway in the choice of the crossover point and, thus, in the angular sensitivity of the system. Crossovers at very low power level result in loss of sensitivity because too little energy hits the target proper. Also there is chance of confusion because excessive amounts hit confusing targets. Crossover at peak power, on the other hand, obviously results in complete loss of angular sensitivity. This problem too is tied in with the stability of the airplane during the approach, because excessive sensitivity results in off-target indications over too large a fraction of the time. Thus a study of the stability of the airplane during the approach, that is, of the apparent angular deviations of the target from the cross hairs both in time and magnitude, is important in the determination of the optimum operating conditions.

Finally, the best values of time constants in the system should be investigated. If taken over sufficient time, the average deviation of the target from the optical cross hairs will be small because the pilot is constantly trying to fly his plane so that the target is centered. Therefore an increase in the time constant can, to a certain extent, overcome the troubles introduced by a very narrow beam or an excessive angular sensitivity. Long time constants, however, make the system sluggish; this is operationally unsatisfactory.

As was pointed out, these factors are interrelated and the optimum set of conditions may therefore be expected to be a region rather than a mathematical point, and it may involve compromises.

The existence of these factors was realized during the work on Vulture and Terry. At that time, however, speed was so essential that existing units had to be used, even if it was well known that the beamwidth was excessive. Plans for an investigation as outlined were made, but never carried out because of the lack of manpower. It is sincerely hoped that the armed forces will be able to give this problem the thorough analysis it certainly needs.

20.7.3 New Combinations

A review of the radar equipment in use at the end of World War II on fighter and fighter-bomber airplanes reveals a multiplicity of radar systems. There are, for instance, ARO, AN/APS-4, AN/APS-19, Falcon, Vulture, Terry, and several AI systems. The question arises whether these cannot be consolidated. Since the advent of the new radar techniques described in this chapter, such as the V presentation and the Terry system, possibilities indeed exist of combining all these functions in a single radar set of acceptable weight and size. The requirement of search demands a scanner that will scan over at least a sector of 60 degrees each side of dead ahead; the requirement of ranging over land and that of blind firing demand one that will produce a conical scan; those of AI demand a spiral scan.

An antenna that will perform these functions can be obtained by small modifications of the AN/APS-19 scanner which has all but the conical scan. The latter can be obtained by arresting the nod, which produces the spiral, at the desired offset.

The r-f, modulator, and receiver sections of such a system can be conventional, but range-tracking circuits as described in this chapter have to be added and special attention given to the indicator. The search function can be presented in a B presentation or in a triangular presentation which will reduce distortion of the shape of landmarks. The presentation for Vulture operation is as described above, except that the presentation will be turned 90 degrees so that range reads up, just as in the B presentation for search. For AI interception and for blind firing and approaches, the 2:1 frequency reduction in the multivibrator is changed to a 1:1 ratio. With proper phasing this results in a presentation as shown in Figure 21. The vertical strips correspond to left-up–right-down positions of the scanner, and appearance of a target response in one of these quarters shows directly which way the plane has to be moved to make it point at the target. Appearance of a response on a dividing line means that the target is, for instance, up and to the right.

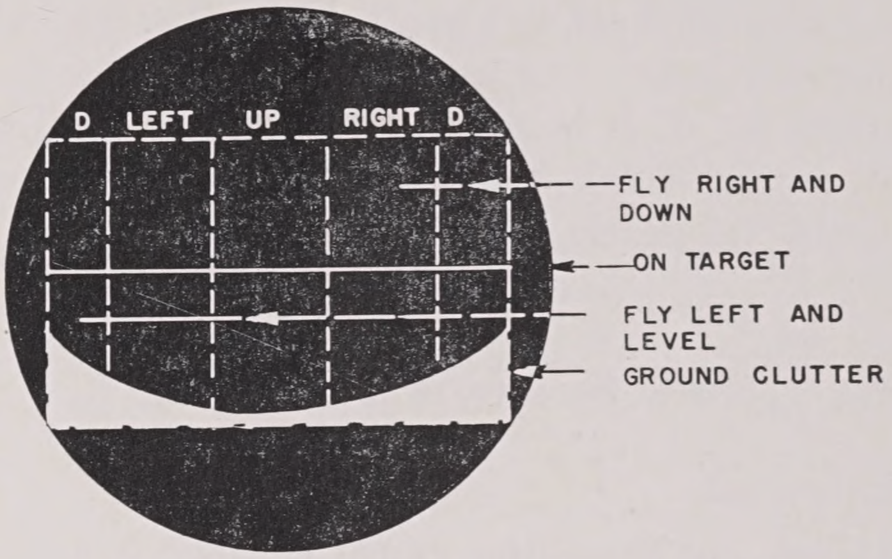


FIGURE 21. V presentation for AI.

This interpretation is independent of the degree of offset of the scanner; therefore the presentation can be used for spiral-scan AI search, as well as for a firing run or an approach on an airfield or beacon (or on isolated targets obscured by cloud layers). It has the advantage of all panoramic presentations, that is, of showing returns from more than one target without upsetting the information from the desired one. As a result, ground clutter can easily be recognized as such. A further advantage is that no change in presentation is needed when going from search to attack. The possibility of using this presentation for blind approaches was demonstrated with a Vulture set in a number of approaches on a lighthouse in Boston harbor. Sperry was informed of the possibilities of this presentation for their AN/APS-19 radar, and made similar runs which confirmed the earlier results.

The pilots would have to learn the interpretation of this presentation, but this should cause no trouble. In the investigation of the optimum parameters, described in Section 20.7.2, attention should be given to measurement of the angular deviation needed to produce a clear off-target indication in this system of presentation. Other presentations are possible, but this one seems to promise the greatest simplicity in equipment.

The ARO and Terry tracking functions can be as described under the Terry system. One investigation was made and showed that an ASH system could be modified to do this job on a crash program basis[51] but a development started from scratch would be far better.

As a result of discussions with Navy personnel, the Navy decided to set up a new type number AN/APS-25 for such a set, and has prepared tentative specifications for it. It is hoped that this work will proceed, as such a set should be perfectly possible and be usable for nearly all tactical problems.

20.7.4 New Systems and Parts

1/*R* SYSTEMS

At least one computing gunsight which is in an advanced state of development, the Draper-Davis or A-1 sight, could be appreciably simplified if the radar set would put out $1/R$, the reciprocal of range, instead of range itself. Proposals have been made to obtain such a set by using the returned signal echo to retrigger the modulator. This would give a variable repetition rate, the recurrence frequency being proportional to $1/R$. At short ranges this would result in very high recurrence frequencies and thus in high duty cycles for the transmitter tube. At the same time, the power needed at short ranges would be low, and this condition does not appear to offer fundamental difficulties.

A system of this type would completely eliminate all the range-tracking circuits now used in the ARO set and in addition would eliminate the servo follow-up and the R to $1/R$ conversion cam in the sight-computer. Some simple extensions would also permit the use of such a system for the operations now performed by the Terry system.

No work has been done on this system beyond some preliminary rough calculations, but in view of the possible saving in weight and complexity, further work along this line seems desirable.

SIMPLIFIED RANGE CIRCUITS

Some circuits have been proposed[51] which might perform the functions of the ARO range-tracking system with considerably fewer tubes. They should receive careful consideration, particularly for use in a lightweight set such as the proposed AN/APS-25.

SMALL ANTENNAS

The present conical-scan antennas, requiring a radome approximately 17 in. in diameter, still present a serious problem in installation and in drag. It is conceivable that jet-engined fighters such as the P-80 may find room in the nose to install the radar antenna. Some conventional planes may carry the radar in a detachable streamlined nacelle under the wings or the fuselage, although the latter may result in trouble from propeller modulation, caused by the propeller intercepting part of the radar beam and thus modulating the signals in a spurious fashion. In general there is a definite need for antennas that will have low drag and easy installation. Such an antenna may be made possible by the use of polystyrene rods. They can be shaped so as to have a paraboloid radiation pattern and yet have the advantage of being long and narrow. Thus they have very little drag and can be installed in the leading edges of the wings. In order to obtain conical scan, such a polyrod antenna should be offset from the longitudinal axis and rotated around it.

An antenna which switches lobes in elevation has been proposed for use with Vulture and Terry systems in place of the conical scan. The fundamental difference in performance of the two antennas is that the lobe-switching antenna greatly decreases the modulation placed on the desired target's echo by targets at the same range to the left and to the right of the desired target. The angular sensitivity of the Vulture system with conical scan is roughly 0.5 degree. Left-right targets more than 0.5 degree away from the desired target will introduce modulation on the desired signal echo. In a straight approach to a ground target, the total ground distance to left and right of the target over which unmodulated signal return would be obtained is less than 100 yd throughout the entire run. A lobe-switching antenna whose pattern and crossover are the same as the conical-scan antenna for the up-down positions would give an unmodulated return from left-right targets out to distances beyond half power for a range differential of less than 100 yd throughout the run. The effect of sloping or rough terrain and of banking of the aircraft is to reduce these side distances. Other effects are negligible.

Preliminary investigations indicate that a lobe-switching antenna can be constructed of two pieces of polystyrene or similar material shielded one from the other by an H-shaped reflector. The upper half will have a pattern corresponding to beam-up, the lower to beam-down. Power can be transmitted on both halves at the same time, but received power is switched from one to the other, so that a single receiver will suffice. Satisfactory switches using modified TR tubes have been developed.[27, 31] At X band such an antenna would be about 7 in. long, 2 in. high and ¼ in. wide.

Chapter 21

COMPUTER PROBLEMS

21.1 THE ROLE OF RADAR IN AERIAL COMBAT

21.1.1 Survey of Preradar Bomber Gunnery

At the beginning of World War II, little attention was given to armament for bombardment aircraft. However, losses from fighter attacks soon forced attention to defensive measures. The British solution was based on night operation, whereas the AAF favored day operation in tight formations with fighter escorts. However, the addition of turrets and other gun positions became a "must" in all bombers.

The Lead Problem

It soon became apparent that merely having guns was not enough. To hit an attacking fighter plane, except in a stern chase, requires careful aiming. If a bomber gunner at A (see Figure 1A) wishes to hit an attacking fighter then at B, he must aim so that his bullet goes in the direction AC where C is the place the fighter will be t seconds later, t being the time required for the bullet to go from A to C. To achieve the bullet line AC it is necessary to point the gun along the line AD. The angle L between AB and AD is called the lead angle. Correct aiming requires that the gunner know the lead angle and also in what direction to lay off the lead angle. This means that he must be able to predict the future course of the attacking plane. It is obviously impossible to predict exactly what the fighter's future course will be; the utmost that can be expected is a rough prediction based on extrapolation from the fighter's course up to the time of firing.

Position Firing and Vector Sights

Numerous and widely divergent rules for gunners sprang up, but none of them were very effective until position firing was introduced. Indeed, the gunnery was so bad that in one bomber command only a negligible percentage of the gunners even knew the correct direction in which to lead. It is clearly impossible to construct any set of practical firing rules that will work for all cases; however, if it is assumed that the attacking fighter is flying a pursuit course then L (see Figure 1A) is given approximately by the formula (called the "own-speed lead" formula)

$$L = \frac{\text{Bomber speed} \times \sin\theta}{\text{Bullet speed}},$$

and the direction of lead is toward the tail of the bomber in the so-called *plane of action* (the plane AEB in Figure 1A).

The term pursuit course here refers to a course which enables continuous fire at the bomber and is more precisely described as an *aerodynamic lead pursuit course.* The development of pursuit course theory started with the classical pursuit course in which the fighter is assumed to stay in a single geometric plane and point directly at a bomber flying straight and level with constant speed. First refinements led to the *lead pursuit course.* Aerodynamics are still ignored, the fighter is still assumed to fly with constant speed in a geometric plane but points his gun enough ahead of the bomber to secure hits; the next improvement was the *aerodynamic pursuit course* in which the fighter is assumed to fly so as to point always directly at the bomber, but the flight path is determined from aerodynamic considerations including such effects as angle of attack (mush) and changes in airspeed. The next refinement was to the aerodynamic lead pursuit course in the determination of which both aerodynamic and ballistic considerations enter. For the theory of aerodynamic lead pursuit courses see reference 77. A companion report [78] contains numerical data for a number of such courses.

Note that in the above formula L depends only on the angle off (angle θ in Figure 1A) of the fighter and is independent of the range to the fighter; thus in using it the weakest point of preradar gunnery, namely, range estimation, is avoided.

Position firing rules exploited the above formula for L; under them the gunner was instructed to lead the fighter in a direction toward the bomber's tail and in an amount proportional to $\sin\theta$. More precisely the range of values for θ was split into several zones, an average value of L was determined for each zone, and the gunner was instructed to use this value throughout the zone.

Aside from a few trimmings which are not discussed here the vector sight was a mechanization of the lead formula used in position firing. It simplified

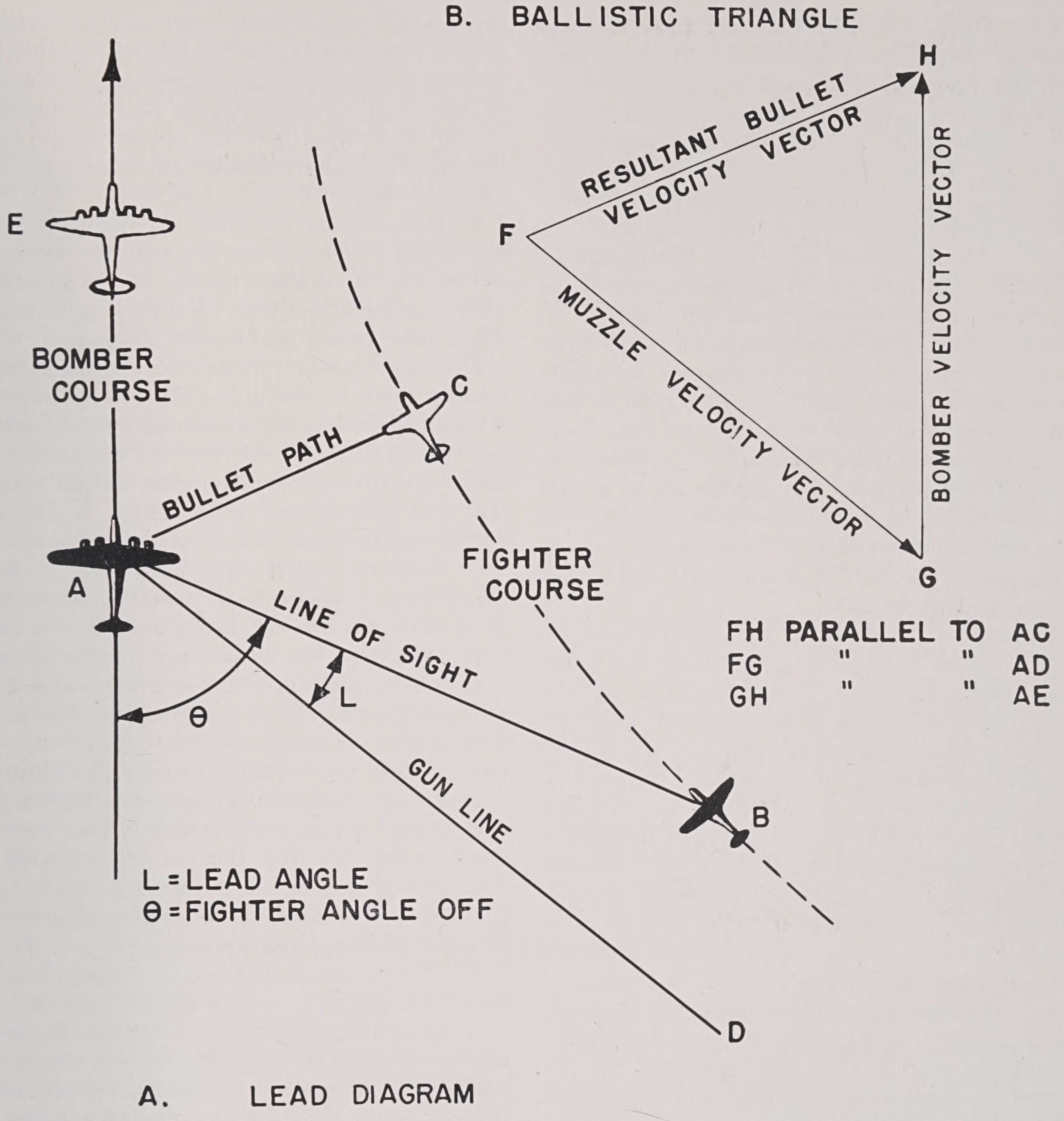

B. BALLISTIC TRIANGLE
H
RESULTANT BULLET VELOCITY VECTOR
F
MUZZLE VELOCITY VECTOR
BOMBER VELOCITY VECTOR
G
FH PARALLEL TO AC
FG " " AD
GH " " AE
E
BOMBER COURSE
C
BULLET PATH
A
FIGHTER COURSE
LINE OF SIGHT
L
θ
GUN LINE
B
L = LEAD ANGLE
θ = FIGHTER ANGLE OFF
D
A. LEAD DIAGRAM

Figure 1. Lead angle for a bomber under attack by a fighter (distances and angles not to scale).

the gunner's problem through automatically deflecting his line of sight by the appropriate position-firing lead. This reduced the gunner's job to positioning his gun so that the target was centered in his sight and then pulling the trigger.

All this simplicity was not without cost. The approximation to L by the own-speed lead formula is rather rough even for pursuit attacks and is absolutely worthless in all other cases. For instance, if one bomber in a formation is being attacked by a fighter then only the gunners in the bomber under attack can hope to hit the fighter using position firing rules; for support fire from other bombers in the formation the formula for L is entirely different. In this connection, however, see a memo [80] giving rules for support fire with a vector sight.

The whole problem of vector sights and position firing has been treated in considerable detail in publications of the Applied Mathematics Panel and Section 7.2 NDRC. [8, 67–69, 88b,c]

Rate Sights with Stadiametric Ranging

Less rough formulas for L than those used for position firing rules or for vector sights give L as a function of R, α, $\dot{\alpha}$, ϵ, $\dot{\epsilon}$ where R = range to target = AB in Figure 1A, α = target azimuth angle, ϵ = target elevation angle, and dots represent time derivatives. For still more precision additional derivatives are used. A very thorough analysis of the lead problem has been made, giving various formulas for the lead.[63, 88] The derivatives $\dot{\alpha}$ and $\dot{\epsilon}$ can be computed by gyros or other rate measuring mechanisms on the assumption that the gunner tracks the target.

Sights based on such formulas require much more from the gunner than a vector sight does. Tests have shown that although gunners can track fairly well, their estimates of range are very poor. Direct estimates of range in the air are likely to be in error as much as 100 per cent; the importance of a good range input can be judged from observing that L is, to a first approximation, proportional to R; so a given percentage error in range results in an equal percentage error in lead.

Stadiametric ranging was one solution that was tried. For this the sight is provided with a reticle whose size is controlled by two dials. One of these dials is preset according to the wing span which the target airplane is known to have, and the other is adjusted continuously throughout an attack so as to keep the sight reticle the same size as the target image. This second dial is the range dial and feeds R (or some function such as $\log R$) to the computer. The range dial may be controlled in many ways, including rotation of handlebar turret controls, foot-pedal controls, or a reversible motor drive controlled by a push button. Division 7 NDRC has sponsored extensive studies of the comparative merits of various ranging (and tracking) methods, and the British carried out similar (but less extensive) studies. Camera assessments of foot-pedal ranging by RAF fighter pilots resulted in claims of accuracy within 10 per cent out to 600 yd, with a rapid decline in accuracy as ranges increased beyond 600 yd. American experience gave less satisfactory results, errors of 50 to 100 per cent being common at moderate ranges.

21.1.2 Range-Only Radar for Bomber Gunnery

A second solution to the ranging problem was the use of radar range, such as ARO described in Chapter 20 or AGS as described in Chapter 19. There were not many radar-range-plus-optical-sight installations in bombardment aircraft during World War II. Some of the reasons for this lack of use are discussed in Section 21.3 and in Chapter 22. Our immediate concern is a comparison of stadiametric and radar ranging. Proponents of radar range have used the following arguments.

1. Radar range does not depend upon target identification. This relieves the gunner of the necessity for setting in target wing span before an attack. Moreover, gunner errors in identification can lead to substantial errors in stadiametric ranging.
2. Radar range is more accurate than stadiametric ranging (even assuming correct target wing-span setting). In practice the gunner cannot give continuous attention to ranging and so will tend to approximate true range by a step function. It is also claimed that even when giving full attention to ranging a gunner cannot get the accuracy of radar range.
3. Radar can supply range information for much greater ranges than can be obtained stadiametrically. It is physically impossible for a gunner to range stadiametrically for ranges beyond the limit of camera measurements, which is approximately 1,000 yd. But, whereas film assessments are made on the ground with unlimited time for precise measurements, stadiametric ranging during flight requires split-second attention, and so physiologically a gunner cannot be expected to match camera performance. In contrast with this the present ARO (or AN/APG-5) is designed to measure ranges up to 2,000 yd, and performance to far greater ranges can be expected from future systems.
4. With the function of ranging removed from his duties, the gunner's tracking should be better.

So far as the author knows, no tests for the merits of the first claim have been carried out. The second and fourth claims have been examined under various test conditions, for example at Eglin Field and the University of New Mexico. The results [83, 94] substantiated (2) but failed to give much support to (4). However, no combat checks have been reported, and it is an important part of the argument in favor of automatic equipment in general that because of psychological reactions a gunner's performance under combat conditions may deteriorate considerably from that in training or under test conditions. The automatic equipment has no psychology and so will do as well in combat as in test. This contention has had ample verification in bombing where combat average radial error ran as high as ten times practice radial error.

21.1.3 Radar Tracking for Bomber Gunnery

There is as yet no tracking radar for bomber gunnery which is superior to visual tracking at its best. However, there are times when optical sighting is impossible and then there is no question of the need for radar tracking. The instances of combat at night, or in clouds are perhaps the most prominent; another instance that came up during World War II was tracking through the vapor trail of a high-flying bomber.

The function and some of the limitations of tracking from a scope presentation of target position are discussed in Chapter 19. Most of the merits of AGS were related to wartime development conditions; it is not the kind of system one would choose to develop under peacetime conditions except possibly for tail-warning-only in aircraft where space and weight limitations preclude use of AGL. An AGS set is useful only when optical sighting is impossible and even then does not have the potentialities of a system which is fully automatic in its tracking operation. In view of these facts only fully automatic radar is included in the following comparison of radar tracking and optical tracking; the discussion is also limited to cases of good visibility, since otherwise there is no competition.

One important factor is the comparative accuracy of radar and optical tracking. Here the situation is greatly influenced by additional considerations, such as (1) the nature of the sight, (2) whether the tracking requires positioning a heavy turret or merely a comparatively lightweight director sight, and (3) the angular rate of the target. No airborne radar system yet designed can establish the line to target at firing ranges as accurately or quickly as a trained operator handling a conveniently mounted lightweight director sight (such as the GE standard B-29 pedestal sight would be if more conveniently mounted). If, however, the line of sight is controlled by positioning a heavy turret, the radar performance may well be fully as accurate as optical tracking. Furthermore, radar systems can begin tracking at ranges too great for optical sighting even under ideal conditions.

Another factor is the importance of smooth tracking. For some sighting systems, smoothness of tracking is absolutely essential, whereas others are rather insensitive to roughness provided the line-of-sight error is kept small. This was borne out by tests at Austin, Texas, carried out by Division 7.2 NDRC on their testing machine.[17a] (See Section 22.3.1.) Whereas the standard B-29 computer required smooth tracking to build up leads, the Mk 18 seemed to function best when the absolute tracking error was minimized, regardless of roughness in tracking (provided the gyro did not tumble). Typical radar tracking has a high-frequency but low-amplitude "jitter"; future developments promise to reduce this jitter sufficiently that smoothing with a very small time constant will give results acceptable for almost all computer requirements.

Although radar tracking cannot (at least for the present) hope to surpass optical tracking at its best in accuracy and smoothness, it might turn out to be superior under combat conditions. A machine is not disturbed in its functioning by a bullet which "almost hits it," whereas some gunners might not track so accurately and smoothly under fire as in practice.

One factor in which radar tracking has a natural advantage over optical tracking is in space requirements. A radar antenna can be placed where a man could never place his eyes. Several radar antennas could give coverage in all directions and could be coordinated in such a way that a target which left the zone of coverage of one antenna could be automatically picked up by another antenna. Attempts to have B-29 gunners coordinate their efforts in this way met almost complete failure. The inherent superiority of machine over man is obvious in this case.

21.1.4 Radar for Fighter Gunnery

The lead for the fighter attacking a bomber on a pursuit course is almost the same as that needed by the bomber's gunner in defending against that fighter. However, the fighter has no such easy solution as a vector sight. For instance, the leads given by a vector sight depend upon bomber speed and angle off of fighter, both of which are relatively accessible to a gunner in the bomber. But an attacking fighter pilot must guess at the bomber's speed and estimate θ (Figure 1A) by comparing apparent length of the bomber's wings and fuselage, or some equivalent feature which depends on angle off. Actually, some fighter pilots became so well versed in pursuit course tactics that they needed only to make certain of starting the attack at the correct position and could from then on fly by rote, just as a concert pianist plays without the score. Obviously, such performance cannot be expected of the average fighter pilot and so does not eliminate the need for computing sights.

If the fighter plane has a rate sight with stadiametric ranging, the pilot must again estimate θ in order to range properly. For whereas stadiametric ranging for the bomber's gunner involves framing a fighter approaching head on, the fighter pilot approaching at a 60-degree angle off gets proper range by having the bomber wings fill just half of his reticle, and at 90 degrees must use fuselage length instead of wing span. A fighter pilot is burdened with far more duties in addition to shooting than is a bomber gunner, and so has less time to do all of these additional things necessary in stadiametric ranging. Some of the problems of the fighter pilot have been studied and summarized.[93, 102]

These considerations lead to the conclusion that radar range is even more important in a fighter sight than in a bomber sight, at least so far as fighter-versus-bomber combat is concerned.

However, in World War II, far more AAF and Navy fighter combat was against enemy fighters than against enemy bombers. Fighter-versus-fighter combat brings in entirely different lead problems. The maneuverability of both target and attacker makes untenable many of the assumptions on which bomber gunsights are based. This tactical condition gave rise to doubts as to the advisability of installing even computing gunsights in fighters, much less radar range for these gunsights. As one naval officer put it, "Fighter combat in the Navy is largely a matter of pot shots following maneuvers for position in a dog fight." Almost all fighter-versus-fighter kills were made from the tail cone. It is to be expected that future fighters will carry some kind of tail armament, and then there will be an undisputed need for computing gunsights and radar range. As the combat aircraft become faster, larger, and more complex in general, the distinction between fighter-versus-fighter and fighter-versus-bomber combats may become smaller, and overall protective armament will be needed in both fighter and bomber.

The problems of the night fighter were treated in Part III and so have not been included in the present chapter, excepting in so far as the fire-control problems of a turreted night fighter resemble those of a bomber.

21.2 RADAR FOR AIR-TO-GROUND COMBAT

As the war developed, the functions of fighter planes were greatly expanded, mostly in the direction of operations against ground targets. The most obvious instance of air-to-ground combat was strafing, a holdover from World War I, and a mode of attack which required no special equipment. It was found that bombs could be hung on a fighter plane; indeed, the P-38 could carry almost as heavy a bomb load as a medium bomber, with the added advantage of being effective as a fighter as soon as the bombs were dropped. Many methods were devised for dropping bombs from fighters or fighter-bombers. These included toss bombing (discussed in Chapter 12), dive bombing, glide bombing, and trajectory bombing.

21.2.1 Ballistic Radar Calibration for Cannon Fire

In line with a trend toward heavier aircraft armament the B-25H and later the A-26 aircraft were designed to carry a 75-mm cannon. At first, the accuracy of cannon fire from an airplane was a disappointment to backers of the installation. It seemed likely that the AAF would drop the cannon-equipped aircraft, when the advent of Falcon (AN/APG-13A), a radar system designed to supply range from an airplane to an isolated water target, changed the situation. The sighting system used with Falcon is extremely simple, although it requires a radar operator in addition to the pilot. This system is described in detail in the Falcon manual [33] and in somewhat less detail in a later report.[72] (See also Section 20.4.2.) The target appears to the radar operator as a pip on an M scope. He tracks the target in range by keeping a crank-controlled range-step in coincidence with the target pip. His crank is connected by a flexible shaft to a ballistic cam which positions the sight through which the pilot looks in aiming his aircraft at the target.

The simplicity of the system is achieved only by limiting tactical conditions. Only one set of ballistic data can be put on the cam. This means that correct aiming is achieved only when a firing run begins at a specified range and altitude, with a specified airspeed and throttle setting. No account is taken of temperature effects; and the only provision for wind or target motion is a change in point of aim by the pilot. However, the aiming system proved to be very effective under the conditions for which it was designed. Some of the pilots were consistently able to score over 60 per cent hits on a simulated ship target.[122]

The limitations of the sighting system were brought into focus with the development of Vulture (AN/APG-13B), an air-to-ground ranging system not limited to water targets. This brought a new variable — target altitude — into the picture and provided an impetus for a reconsideration of the whole aiming system, with particular reference to the possibility of making use of a "fudged" range obtained by changing the calibration of the radar set. This adjustment, called ballistic calibration and the accompanying ballistic studies, are described in an Applied Mathematics Panel Report.[72]

The standard calibration of Falcon and Vulture consists of matching two variables: R, the slant range to target, and r, the range supplied to the cam. The mechanical and electrical connections between them guarantee that regardless of calibration r is a linear function ($r = aR + b$) of R. The system can be calibrated so as to achieve any value for a and b (within certain limits), the case $a = 1$, $b = 0$ representing standard calibration. A slide rule calculator, with scales for airspeed, temperature, and altitude is supplied to the radar operator for making the computations incidental to ballistic calibration. Specifically, the slide rule computes $r_1 = 1{,}100a + b$ and $r_5 = 5{,}100a + b$ as functions of airspeed, temperature, and altitude. Ballistic calibration consists of matching the values r_1 and r_5 of r with the values 1,100 and 5,100 of R. The Vulture-cannon combination has a good test record[72] (see Chapter 20), but was developed too late to see combat service.

In spite of the good test record of ballistic calibration it had some important limitations which in the author's opinion preclude its use as more than an interim device.

1. The pilot cannot read correct range to target from the range dial (adjacent to his sight). This is a definite handicap if he intends to follow the cannon firing by strafing, or if he is flying close to the ground and wishes to pull out at a given range.
2. There is no provision for wind or target motion.
3. It is necessary to decide tactics in advance, since the radar operator cannot very well calibrate during the firing run. This is perhaps one of the most serious limitations.
4. There is only a two-parameter adjustment provided to care for changes in correct lead arising from a large number of variables. By restricting the variety of attacks and neglecting some of the less important variables it was possible to achieve much greater accuracy with ballistic calibration than had been hoped at first. However, even though use of ballistic calibration as compared to standard calibration in some cases cuts down errors from 20 to 2 mils,[72a] the errors remaining in others are still large enough to condemn the device for anything more than interim use. The limitations could all be avoided by introduction of a computing unit whose inputs could be range (and perhaps also range rate) from Vulture, dive angle, altitude, airspeed, and temperature.

21.2.2 Miscellaneous Information on Airborne Rocket Sight Settings

Some of the major developments of World War II were in the field of rocketry. The early airborne rockets had such high dispersion that elaborate sighting systems for aiming were not worth while. As the dispersion was progressively reduced, the combat usefulness of the rockets increased and so did the demand for good sighting equipment.

In considering the possible applications of radar ranging to rocket fire control, it is useful to have a rough overall view of the factors affecting the rocket fire. More complete discussions are to be found in publications of Division 3, NDRC, and of the Applied Mathematics Panel.[1, 3–7, 70, 71, 112]

In the simplest case, where the correction for parallax due to the vertical distance between sight and rocket launcher is neglected, and where the launchers are assumed to be parallel to the zero sight line and the level line, the sight setting, following the theory developed at the California Institute of Technology [CIT], is given by (see Figure 2)

$$S = M + f\alpha$$

where S is the sight setting in mils, M is the trajectory drop in mils, f is the rocket ballistic factor,[133] and α is the effective angle of attack of the level line, in mils.

It should be noted that this quantity is not the same, in general, as the angle of attack as determined by wind-tunnel tests. From aerodynamic theory the angle of attack of any fixed line in the airplane can be represented in the form

$$\alpha = \frac{CW \cos \delta}{V_i^2} - K$$

where W is the weight (in pounds), δ is the dive angle, V_i is indicated airspeed, and C and K are constants.

The airplane manufacturer supplies values of these constants. When these values were used in rocket fire it was found that errors of approximately constant value in mils occurred. This was taken care of in the CIT tables for rocket fire from various airplanes by giving new values to the constant K, leaving C unchanged. Thus one must speak of the value for α used in rocket fire as the effective angle of attack for rockets; correspondingly one should speak of an effective flight line. The whole theory is in an incomplete state. Some unpublished calculations by the Applied Mathematics Panel and the Radiation Laboratory show that if the angle of attack term is large and if accurate long-range firing is desired, direct experimental determination of the whole $f\alpha$ term is probably necessary.

When parallax is considered, a term $1{,}000D/R$ mils must be added, where R is the range to the target and D is the vertical distance from sight to launcher, in yards; and if the launchers are set at an angle L mils above the level line (zero sight line) then the small, approximately constant, term $(1 - f)L$ mils must be subtracted from the sight setting.

The following tables give the variations in the two important terms, M and $f\alpha$. The importance of the latter term arises from the fact that, unlike a shell, a fin-stabilized rocket tends to turn into the relative wind, following the line of flight rather than the line of the rocket launcher. Errors from any one source of less than 3 mils are regarded as negligible, with rockets as they now are made.

Table 1 shows some values of the trajectory drop, M, and of the differences, ΔM, for 5-in. *high velocity aircraft rockets* [HVAR] and for 11.75-in. rockets (Tiny Tims). These values are, of course, independent of the type of airplane. Table 1A gives the minimum trajectory drop for each rocket (reached when dive angle, true airspeed, and temperature are maximum);

TABLE 1. Effect of changes in range R, dive angle δ, true airspeed V, and temperature T, upon rocket trajectory drop M. Values of M and ΔM are in mils, based upon CIT tables.

				5″.0 HVAR					11″.75 AR				
		R (yd)		500	1,000	2,000	3,000	4,000	500	1,000	2,000	3,000	4,000
A. Minimum M		$\delta = 60°$	M	8	11	18	25	33	10	15	25	35	44
ΔM for 1,000-yd intervals		$V = 400$ k	ΔM			7	7	8			10	10	9
		$T = 100$ F											
B. Maximum M		$\delta = 0°$	M	38	50	73	99	130	46	68	107	147	190
ΔM for 1,000-yd intervals		$V = 200$ k	ΔM			23	26	31			39	40	42
		$T = 0$ F											
C. Intermediate M		$\delta = 20°$	M	23	32	50	70	91	29	45	73	101	130
ΔM for 1,000-yd intervals		$V = 240$ k	ΔM			18	20	21			28	28	29
		$T = 70$ F											
D. Changes in dive angle only. ΔM for 20° intervals	$V = 240$ k	$\delta = 0°$	M	25	35	54	77	104	31	42	69	80	103
			ΔM	2	3	4	7	13	5	6	6	7	8
		$\delta = 20°$	M	23	32	50	70	91	26	36	54	73	95
	$T = 70$ F		ΔM	5	6	11	16	21	3	4	4	3	4
		$\delta = 40°$	M	18	26	39	54	70	23	32	50	70	91
			ΔM	6	9	14	20	26	2	2	3	3	2
		$\delta = 60°$	M	12	17	25	34	44	21	30	47	67	89
E. Changes in true airspeed only. ΔM for 100-k intervals	$\delta = 20°$	$V = 200$ k	M	26	35	54	75	98	33	50	81	111	143
			ΔM	6	7	10	14	17	8	11	18	23	30
		$V = 300$ k	M	20	28	44	61	81	25	39	63	88	113
	$T = 70$ F		ΔM	4	5	8	10	13	6	9	13	18	22
		$V = 400$ k	M	16	23	36	51	68	19	30	50	70	91
F. Changes in temperature only. ΔM for miscellaneous intervals	$\delta = 20°$	$T = 0$ F	M	31	42	60	80	103	37	54	84	113	142
			ΔM	5	6	6	7	8	4	5	6	7	7
		$T = 40$ F	M	26	36	54	73	95	33	49	78	106	135
	$V = 240$ k		ΔM	3	4	4	3	4	4	4	5	5	5
		$T = 70$ F	M	23	32	50	70	91	29	45	73	101	130
			ΔM	2	2	3	3	2	1	2	1	0	0
		$T = 100$ F	M	21	30	47	67	89	28	43	72	101	130

Table 1B gives the maximum trajectory drop (minimum dive angle, true airspeed and temperature); Table 1C gives a representative intermediate case. Tables 1D, 1E, and 1F show the way in which the trajectory drop varies when only one of the variables is allowed to change, the other two being held constant at the intermediate values.

Tables 2 and 3 show the spread in values of the $f\alpha$ term for a heavy airplane (B-25) and for a light airplane (P-51), using 5-in. HVAR only.

Table 2. Values of f and $f\alpha$ for a B–25 airplane ($C = 125$, $K = 70$ mils, $W = 33{,}000$ lb) firing 5″.0 HVAR.

	T	Indicated airspeed V_i in knots		
		200	240	280
A. Values of f	0 F	0.83	0.89	0.93
	40 F	0.78	0.85	0.90
	70 F	0.76	0.82	0.86
	100 F	0.72	0.80	0.85
B. Values of α when $\delta = 0°$		8	−16	−30
C. Values of $f\alpha$ when $\delta = 0°$	0 F	7	−14	−28
	40 F	6	−14	−27
	70 F	6	−13	−26
	100 F	6	−13	−25
D. Change in $f\alpha$ per 1,000-lb change in wt when $\delta = 0°$		2	2	1
E. Values of α when $\delta = 20°$		3	−19	−33
F. Values of $f\alpha$ when $\delta = 20°$	0 F	3	−17	−31
	40 F	2	−16	−30
	70 F	2	−16	−28
	100 F	2	−15	−28
G. Change in $f\alpha$ per 1,000-lb change in wt when $\delta = 20°$		1	2	1

The effects of various kinds of errors are summarized below.

Range Errors

As will be seen from the table, an error of 100 yd in range produces an error of 1 to 4 mils in sight setting; this error is almost independent of range.

Dive Angle Errors

A change in dive angle produces a change in sight setting which is approximately proportional to range. At 3,000 yd, a 1-degree change in dive angle produces a change of 0.5 to 1 mil in sight setting for the 5-in. HVAR.

Table 3. Values of f and $f\alpha$ for a P–51 airplane ($C = 250$, $K = 24$ mils, $W = 9{,}500$ lb) firing 5″.0 HVAR.

		Indicated airspeed V_i in knots			
		240	300	360	420
A. Values of f	0 F	0.84	0.91	0.95	0.97
	40 F	0.79	0.88	0.93	0.95
	70 F	0.77	0.84	0.89	0.92
	100 F	0.73	0.83	0.88	0.91
B. Values of α when $\delta = 0°$		34	13	2	−5
C. Values of $f\alpha$ when $\delta = 0°$	0 F	29	12	2	−5
	40 F	27	11	2	−5
	70 F	26	11	2	−5
	100 F	25	11	2	−5
D. Change in $f\alpha$ per 1,000-lb change in wt when $\delta = 0°$		5	3	2	2
E. Values of α when $\delta = 30°$		26	8	−2	−8
F. Values of $f\alpha$ when $\delta = 30°$	0 F	22	7	−2	−8
	40 F	21	7	−2	−8
	70 F	20	7	−2	−7
	100 F	19	7	−2	−7
G. Change in $f\alpha$ per 1,000-lb change in wt when $\delta = 30°$		4	3	2	2
H. Values of α when $\delta = 60°$		5	−5	−11	−15
J. Values of $f\alpha$ when $\delta = 60°$	0 F	4	−5	−10	−15
	40 F	4	−4	−10	−14
	70 F	4	−4	−10	−14
	100 F	4	−4	−10	−14
K. Change in $f\alpha$ per 1,000-lb change in wt when $\delta = 60°$		2	2	1	1

Temperature Errors

Changes produced by temperature variations are only slightly dependent upon range. On the average they amount to about 1-mil decrease per 10-degree rise in temperature, but there is a curious inversion in that for low temperatures the temperature correction increases slightly with range, while at high temperatures it tends to decrease with range.

Airspeed Errors

A decrease in sight setting of from 5 to 15 mils is caused by a 100-knot increase in true airspeed. The change per knot is an increasing function of range.

Altitude Errors

No information is available on the effect of altitude. It is stated that the data are based on observations at 2,500 ft above sea level.

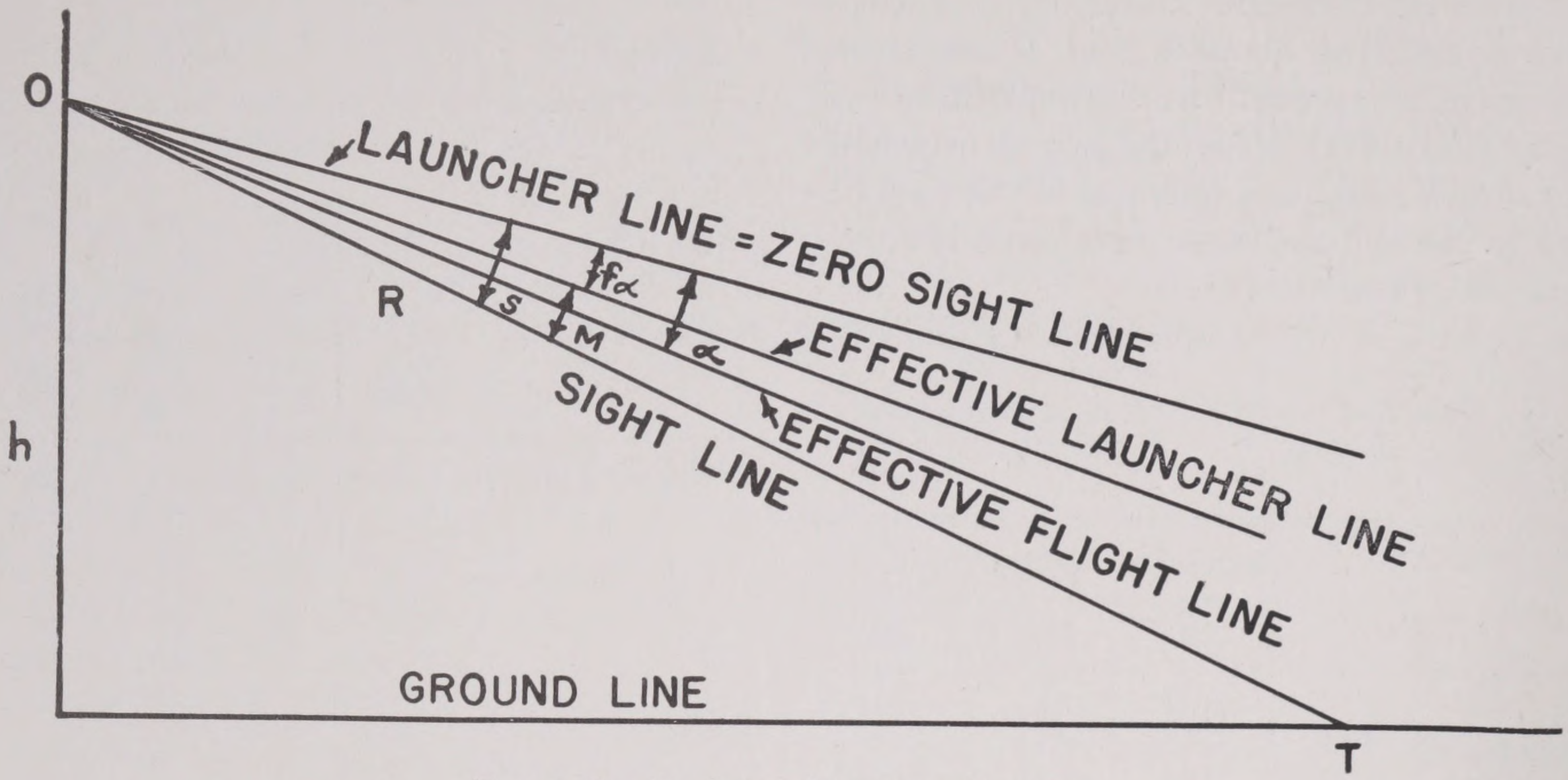


Figure 2. Rocket sight-setting diagram.

Changes in $f\alpha$

The rocket factor f varies from 0.70 to 1.00. It decreases with increasing temperature and increases with speed. For slower rockets it is very close to unity. The angle of attack [133] usually is not above 40 mils (for slow speed and heavy weight). It may become negative at high speeds and high dive angles. In considering what the minimum value of α might be, it is clearly necessary to know the highest practical speed and dive angle. For example, with the B-25 a speed of 400 knots and dive angle of 60 degrees would give an angle of attack of -64 mils, but this situation is obviously impossible. The sample values of the $f\alpha$ term given in Tables 2 and 3 cover fairly wide ranges of conditions.

21.2.3 Radar Ranging for Rockets

One feature of the development of airborne rockets was a shift in requirements from airborne cannons to rockets. There were several good reasons for this shift. As compared with a cannon, rocket launchers have negligible weight. This made it possible to use rockets even on the lightest fighter planes. Rockets take up no space inside the fuselage. The explosive charge of a "Holy Moses" (5″0 HVAR) is several times that of a 75-mm cannon shell. Rockets, unlike cannon, require no loading during flight. This makes it possible to fire rockets from a single-seater fighter plane.

Although airborne rockets appear to be superior to airborne cannon for most purposes, there are certain advantages of the latter which may save it from utter oblivion. In spite of improvements, rocket dispersion remains at present two or three times as great as cannon dispersion, and even the fastest airborne rockets have only about two-thirds the velocity of the 75-mm cannon. These factors result in greater accuracy, smaller leads, and flatter trajectories for cannon than for rockets. There are tactical conditions under which these features of the airborne cannon make it the only effective weapon so far developed. One such condition is shooting into caves, where the flat trajectory and accuracy of the airborne cannon gave it superiority over all other weapons tested.

For applications of radar to rocketry, aircraft fall into three classes.

1. Single-seater fighters. In these planes only automatic radar can be used for fire-control purposes. Space and weight are at a premium, so, unless a radar set makes very definite contributions, it will not be installed.
2. Larger aircraft where no radar operator is available. Radar installations for this class of aircraft are still limited to automatic systems. However, weight and size requirements are no longer so critical.
3. Aircraft with a radar operator available. This does not necessarily mean full-time availability of a radar operator. With semiautomatic ranging, as provided in AN/APG-13B (see Chapter 20), only occasional attention is required by the radar operator. (For instance, in the A-26 with 75-mm cannon, the radar operator was also cannoneer.)

Although it is true that range-to-target is the main variable in determining correct lead for rocket fire, it does not follow that a direct range input is necessary. The tardiness of development of an air-to-ground radar range system, together with the anticipated weight and other requirements of radar, stimulated research on various substitutes for range. The number of rocket sights developed or proposed during the past two years is legion; it is not the author's intention to discuss them here, aside from their methods of calculation of range. Discussion of many of these systems can be found in NDRC publications, especially those of Division 3, Section 7.2 and the Applied Mathematics Panel.[2, 9, 10, 12, 13, 71, 101, 104, 138]

Several of the sights depend on a diving approach to the target; R is then calculated geometrically. Referring to Figure 2, we have $R = h \csc \delta$. Thus, a dive angle indicator and an altimeter can be used to calculate R. Now differentiate with respect to time, recalling that dive angle is constant throughout an attack and get $\dot{R}$ = true airspeed = $\dot{h} \csc \delta$ and thence $R = \dot{R}h/\dot{h}$. In this equation $\dot{h}$ may be supplied by mechanically differentiating h or by observing the change in h during some short time interval. The actual sights do not usually explicitly obtain R; instead the full sighting formula may be written as a function of all variables finally used and mechanized as a whole. It should be mentioned that the quantities used to compute range also enter in other parts of the sighting formula.

Another class of sights made use of the fact that the curvature of a logarithmic spiral, at a point, is inversely proportional to the distance from that point to the origin of the spiral. If an aircraft flies so that the angle β between the line of flight and the line of sight to the target is kept constant, then the path of the aircraft is a logarithmic spiral. Now if on any path the velocity of an aircraft is kept constant, the acceleration normal to the flight axis of the aircraft is proportional to the curvature of the flight path. Thus, if an accelerometer is placed so as to measure only the component of acceleration normal to the flight axis and if the pilot flies so as to keep the target centered on a sight with constant offset β, range can be computed. The sight offset can be either above or below the line of flight, although if it is above, control of the aircraft tends to become sluggish and may make tracking difficult.[98]

Several of the rocket sights developed for fighter planes were very compact and lightweight, some weighing under 30 lb. It is not hard to understand why installation of Terry (AN/APG-21), which weighed about 125 lb, was not regarded with favor unless it could contribute to a sighting system which could do much more than these lightweight nonradar rocket sights. Some possibilities along such lines are discussed in the following section.

However, for aircraft such as the B-25 or the A-26 which are limited to fairly small dive angles, measurement of range from $\csc \delta$ becomes undependable. For this reason, the rocket sights developed for fighter planes were not suitable for use in larger planes. The development of Vulture made it important to design a rocket computer for medium bombers. In particular, at the end of the war, the Radiation Laboratory was developing a rocket computer for use with Vulture in the B-25. This computer, known as the Vulture Rocket Computer,[29] was intended as an interim device, to serve only until more complete computers such as those discussed in the following section would be available.

21.2.4 All-Purpose Sights

A fighter aircraft is expected to perform a wide variety of functions, and each of these requires its own special equipment. Thus there are machine-gun sights, rocket sights, toss-bombing sights, torpedo directors, and cannon sights for fighters and for fighter bombers. The amount of space in the cockpit of a fighter plane does not permit separate installations for each function. Common practice has been to decide which of the functions was primary, to install the equipment for that function, and then to look for ways to use this equipment for the remaining functions. The desirability of having a single sighting system which could handle all of the sighting functions of a fighter or of a fighter bomber became increasingly evident, especially with the increase of emphasis on airborne rockets.

At least two all-purpose sights were under development by the end of World War II, the Draper-Davis A-1 sight [71a,b] and the *pilot's universal sighting system* [PUSS].[12, 13]

Because of uncertainties about the completion date of Terry both the A-1 sight and PUSS had two lines of development, one based on both air-to-air and air-to-ground radar range and the other based on air-to-air radar range but with various substitutes for air-to-ground radar range. So far as the trajectory-drop terms in the rocket leads are concerned, substitutes for radar range may be reasonably satisfactory. However, such substitutes do not allow for the leads due to target motion or wind. It is obviously highly desirable to have a sighting system which is effective in rough weather and against moving targets (such as tanks); this can be achieved if air-to-ground radar range is included in the sighting system. The fact that Terry can serve for both air-to-ground and air-to-air ranging is essential in its application to all-purpose sights.

21.3 COORDINATION OF RADAR AND GUNSIGHTS

21.3.1 General Discussion of Gunsights

This section is written to supply background about gunsights. It is not intended to treat any specific gunsight or theory of gunsights in detail. This has been done in publications of the Applied Mathematics Panel, of Section 7.2, NDRC, of the Army and Navy, and of the computer manufacturers. The following set of references is limited to the first two sources and make no pretense of completeness. [8, 12, 13, 16, 59, 61–66, 74–76, 88, 108, 111, 114]

The simplest sights are ring and post or optical ring sights which are noncomputing. A slightly more complicated sight is the vector or own-speed sight which was discussed in Section 21.1.1. Obviously, none of these sights has any requirement for either radar range or radar tracking.

Next in order of complexity are the rate sights. Such a sight computes the lead L as the solution of a differential equation such as

$$(-a)u\dot{L} + L = u\dot{\sigma} - \beta \qquad (1)$$

where u = time of flight in seconds of bullet to present position (from A to B in Figure 1A),
σ = angular velocity of the line of sight in radians per second,
a = a parameter of the sight; in practice a is between 0 and -1,
β = ballistic deflection (caused by bullet slowdown in flight).

If the gunner is tracking the target, $\dot{\sigma} = \dot{\theta}$ (see Figure 1A) and the term $u\dot{\sigma}$ is the so-called "angular-travel lead," the lead L can be regarded as an exponentially smoothed value of the angular-travel lead plus the ballistic deflection with smoothing time constant $k = (-a)u$. [58a]

The mechanism to measure $\dot{\sigma}$ may be a mechanical or electrical integrator (as in the Sperry K-4 family and the Fairchild K-8) or a gyroscope (as in the Mk 18).

The non-gyro sights are unable to distinguish between motion of the gun platform and motion of the sight head. Consequently pitch, roll, and yaw of the aircraft result in the feeding of false information to the sight. Gyro sights avoid this difficulty, provided the gunner continues to track the target accurately while his plane's course is unsteady. This is apt to be a considerable chore, so the most recent sights have been stabilized, i.e., have automatic compensation for deviations of aircraft from a rectilinear path.

The computation for $\dot{\sigma}$ may be made in components or all at once. The Mk 18 is a single (free) gyro sight which computes $\dot{\sigma}$ directly. The B-29 standard computer is a two-gyro sight which computes in components. The gyro is used entirely differently in these two cases. In the Mk 18, the gyro has a gimbal mounting and is free to precess in whatever direction the forces acting on it require. The amount of precession is controlled magnetically, and is proportional to the lead set up. This is accomplished by attaching to the gyro a mirror whose deflection determines the position of the sight reticle. In contrast with this in the B-29 standard computer each gyro has a single pivotal mount and is thereby constrained to motion in one direction (relative to its case). The amount of motion in this permitted direction is very small, just enough to make a contact which activates a force just sufficient to neutralize the precession force of the gyro. The neutralizing force is measured and thus transmits information from the gyro to the computer.

When $\dot{\sigma}$ is computed in two components care must be taken to avoid errors due to the phenomenon of "gun roll." The mathematical basis of gun-roll errors is the fact that a rotation in space is determined by three parameters (for instance azimuth and elevation of the axis of rotation plus a third parameter giving the amount of rotation) and measurement of angular motion in two components must neglect one of these parameters. If the sighting system is constructed so as to measure the right pair of parameters no error is introduced, but otherwise gun-roll errors are present. A detailed analysis of gun-roll errors is given in Applied Mathematics Panel Studies. [63a, 88]

Lead-computing gunsights can be divided into two classes according to whether the gunner has direct control of the sight line or of the gun line. In a director system the gunner has immediate control of the line of sight and as he tracks the target the computer determines the lead and positions the guns. The standard B-29 computer is a director system. In a disturbed-reticle sight, the gunner has immediate control of the gun line. The sight case is mounted on the gun and the computer positions the line of sight with respect to the gun. The Mk-18, K-3, K-8, and A-1 are examples of disturbed-reticle sights. There are computing sights which are neither directors nor disturbed-reticle sights but lie somewhere between. (For instance in the S-8b, the gunner has direct control of the lead angle rather than either sight line or gun line.)[88d] These intermediate types were not developed in time for use in World War II but seem likely to have considerable future use.

A director sight is evidently operationally simpler for the gunner, but it requires much more machinery with consequent addition of weight, size, and maintenance problems.

In general, director systems are designed for remotely controlled gun turrets, whereas disturbed-reticle sights are used in local turrets.

Problems of operational stability have arisen in the use of tracking radars as components of airborne fire-control systems. Some discussion of these problems appears in Chapters 18 and 19, but much remains to be learned in this field. Some preliminary work along these lines has been done.[88, 89, 139, 140]

21.3.2 Calibration of Computers and the Role of Range Rate

In actual practice a formula for L such as given by equation (1) may be improved if u is replaced by some other quantity v. Since u equals range divided by average bullet velocity, it is primarily a function of R. Replace u by $v = v(R)$ in (1) and solve for v, obtaining

$$v = \frac{L + \beta}{\dot{\sigma} + a\dot{L}}. \tag{2}$$

Now, for any given attack course C, the right-hand side of (2) can be computed giving v as a function $v(R, C)$ of range and of the particular course. If several courses C_1, C_2, $\cdots$ are considered we can compare the corresponding functions $v(R, C_i)$. If the courses chosen are representative, and if some estimate is made of relative importance of these courses, then a weighted average

$$v(R) = \frac{\sum_i w_i v(R, C_i)}{\sum_i w_i}$$

of the functions $v(R, C_i)$ may be far superior to the original time of flight $u(R)$.

The above process for obtaining a function $v(R)$ to use instead of u in equation (1) is an example of time-of-flight calibration. There have been a number of other ways proposed for determining $v(R)$, many of which involve considerable refinements and improvements over the simple one described above. In particular, the use of time-of-flight calibration is not limited to sights which mechanize equation (1); it can be used with any lead-computing sight. In all cases the essence of the process of time-of-flight calibration is to regard the time-of-flight setting $v(R)$ as a function of range whose form is chosen directly with a view to the overall performance of the instrument, rather than to fit ballistic tables.

This point of view was emphasized by Professor Draper first in his antiaircraft sights and later in his aircraft sights. Draper's work has been carried on and extended by I. Kaplansky and other members of the Applied Mathematics Panel. [79, 88, 95, 103, 110]

Some radar systems (in particular f-m sets) give both R and $\dot{R}$ (range rate) as outputs. The possible use of $\dot{R}$ in lead-computing sights was the subject of considerable discussion during the latter part of the war. It is obvious that allowing v to be a function $v(R, \dot{R}, C)$ allows the effective inclusion of more courses C_i in averaging, this time obtaining an average function $v(R, \dot{R})$ to be mechanized.

In particular, it has been suggested that use of both R and $\dot{R}$ as inputs would allow calibration to fit both pursuit courses and straight line courses. But it has also been argued that use of $\dot{R}$ without also using angular accelerations would not be of much advantage. The author's opinion is that the lead-computing sights developed by the end of World War II were not sufficiently accurate to justify refinements such as $\dot{R}$. This is not a reflection on the sight designers, since they were faced with the problem of quickly getting something into production which was better than vector sights or position firing rules, and in this they seem to have been successful. However, postwar developments of lead-computing sights should be based on careful studies of the value of range rate and of angular acceleration inputs, keeping in mind, of course, possible limitations to the accuracies with which these quantities may be measurable in practice. Attention is called in particular to Hestenes' proposal [61] for a vector-rate sight in which inputs of range rate and angular acceleration are included.[110]

21.3.3 Problems in Coordination

One of the early decisions of NDRC was to set up one division for fire control and another for radar.

Section 7.2, NDRC, had responsibility for airborne fire control and Division 9 of the Radiation Laboratory, a contractor of Division 14, NDRC, had responsibility for airborne radar of all kinds. The liaison between these two agencies was intermittent in character although it improved during the last year of the war, too late to have any influence aside from that on postwar developments. The Army and Navy had somewhat similar divisions of responsibility in their agencies. There were gunsight developments under direct Service contracts entirely unrelated to Section 7.2, NDRC, and there were airborne radar fire-control systems under direct Service contracts, entirely independent of the Radiation Laboratory. The net result was a chaotic condition in which there was no single agency with overall responsibility for airborne fire-control systems and this condition was reflected in the lack of progress in getting effective airborne fire-control systems into combat. Perhaps the best way to illustrate the general coordination problem is to treat a few special cases.

In designing the ARO system, it was necessary to decide what form the range presentation should take. A scope presentation requires operator interpretation. Since it was considered essential to have an automatic range signal, only electrical or mechanical outputs were considered.

After a series of conferences it was decided late in 1942 to standardize the ARO output as a direct-current voltage proportional to range. However, the first contracts let were for ARO units to feed range into the Sperry K-4 sight, and as a result of this the ARO units actually manufactured were equipped with gear boxes which converted the output voltage to a shaft rotation proportional to range, one complete revolution for each 100 yards range. Further standardization conferences were held throughout 1943, 1944, and 1945, until finally in the spring of 1945 complete specifications for ARO were agreed upon. Most of the modifications agreed upon in this series of conferences were engineering changes to improve performance but some of them had definite influence on methods of using ARO with gunsights. The sight makers paid almost no attention to these modifications, partly because they were not directly informed and partly because they were not enough interested in being informed. Some of them felt that they should not "waste time" on radar until it was completely standardized.

There were exceptions to this general indifference to ARO. For instance, the K-4 plus ARO combination was carefully nurtured, but unfortunately the K-4 sight was obsolete by the time ARO was ready for use. The Draper-Davis A-1 sight was designed from the outset to accept radar range in the same way as the K-4. Performance of the ARO A-1 system during tests at Eglin Field in 1945 was one of the bright spots in the airborne fire-control program.

Meanwhile other lead-computing sights had been developed without reference to possible use of radar range. The Mark 18 and the General Electric standard B-29 computer were both designed to accept log R rather than R, the former for ranges up to 800 yards, the latter for ranges up to 1,250 yards (ARO is designed to supply range up to 2,000 yards). This difference in maximum range together with other differences makes it impossible to find any single range output mechanism which would fit both of these sights.

When radar range was required for those sights, sight maker, radar maker and other interested parties all sat down together for a series of conferences to decide who should be responsible for the intermediate gear boxes or other gadgets needed to convert from radar output range function to sight input range function.

In the case of the B-29 computer, the radar system used for range was AGS rather than ARO, but this changed nothing so far as combination of sight and radar range was concerned. The first few installations made use of a mechanical gear box, but in later production the computer was modified to accept the standard output of voltage proportional to range and the combat wing described in Chapter 19 was so equipped. The marriage of radar and computer was considerably simplified by the fact that in this case sight manufacturer was also radar manufacturer.

The case of the Mark 18 was much more difficult, because of the fact that the sight required a shaft rotation, whereas in the B-29 computer either shaft rotation or voltage was possible. The sight maker finally accepted responsibility for gear box modifications to convert straight range to logarithmic range and a few gear boxes were available in time for equipping several planes for test purposes and ten planes for combat tests. (These aircraft saw no aerial combat because of reduced enemy fighter action. However, the equipment had a good maintenance record in the combat theater.)

The role of radar in rocketry was discussed above. So far as interim rocket sights for fighters were concerned, the nonuse of radar was fully justified. However, rockets might have been used on medium bombers much sooner than they were if the liaison between sight designer and radar designer had been closer. On the one hand, the radar experts were not aware of the potential value of rockets; while on the other hand the sight experts were so wrapped up in the fighter plane problem, where radar range was not then feasible, that they did not visualize that radar already developed might be useful in other cases. The sighting methods which they had developed for fighter planes broke down for the less maneuverable medium bomber. The sight experts were reluctant to leave the fighter field where sights were needed in thousands to start afresh in the medium bomber field where the total number of sights needed might never have exceeded one thousand. This exclusive emphasis on a major problem resulting in a complete neglect of minor, though still important, problems is in itself a good instance of lack of overall direction of the airborne fire-control program.

Another place where lack of overall direction showed up clearly was in the AGL system programs. The early AGL's, AN/APG-1 and AN/APG-2, were too heavy and bulky for use in bombers. (One small squadron of P-61's equipped with AN/APG-1 and a director type sighting system were headed toward combat at the end of the war.)

The later AGL's were considerably lighter. However, the development of AN/APG-3, which was intended, among other things, to replace AN/APG-15 for the tail defense of the B-29, was delayed for at least a year because of installation problems. The radar set was still too large to fit in the space then available and the aircraft manufacturer was not enthusiastic about redesigning the tail turret to accommodate the radar.

21.3.4 Possible Solutions for the Coordination Problem

There are a number of reasons why coordination problems of the kind described above may be expected to become more severe in the future. The number of functions of an aircraft has been increasing and each new function means new coordination problems. It will not be easy to install anything at all outside the fuselage of the newer very high speed aircraft. Accuracy criteria will become much more severe in the atomic era, since missing even a few enemy planes or missiles might spell destruction for whole cities.

These factors prompt the suggestion that in future developments of the combat airplane, the aircraft manufacturer should have overall responsibility for every piece of equipment his plane is to carry. He would, of course, be at liberty to subcontract, but he would have responsibility for fitting all of the pieces together, from the drawing board stage on. He would be encouraged to draw upon resources of government-sponsored research organizations, and would naturally be expected to meet certain Army-Navy requirements.

The aircraft manufacturer might wish to subcontract for all of the fire-control equipment on his airplane. Suppose, for instance, he wished to subcontract for the tail turret of a bomber, complete with armament, search, and gunlaying equipment. He would then have to design his aircraft with due consideration to all features of tail-turret operation, including, for instance, provision of ample power supply to the turret and all of its equipment, provision for radar antenna installation, allowing for aerodynamic drag of the tail turret and equipment attached outside it. The turret contractor might, in turn, wish to subcontract the gunlaying system. If he gave separate subcontracts for radar and gunsight he would encounter some problems similar to those already discussed; unlike those situations, there would be no lack of authority to make the decisions necessary in solving these problems.

It is clear that the Service agency which placed the contract would have to maintain close contact with the manufacturer, to see that the latter did not merely choose the system which would cause him the least trouble, or which was the most attractive for purely business reasons.

A change from present policy less drastic than assigning prime responsibility to the aircraft manufacturer would be to concentrate complete responsibility in some single Army-Navy agency, so that discussion of engineering details would not have to be carried on at so many different points and with such frequently changing personnel as was usual during World War II. This agency, which would have to possess a high degree of technical competency, and be in close touch with development agencies, would contract separately for the components (aircraft included), with carefully written specifications to reduce problems in coordination.

Chapter 22

ASSESSMENT PROBLEMS

Experience throughout World War II showed that assessment of fire-control systems is not easy. The reports of the Applied Mathematics Panel and of the various Applied Mathematics Groups, particularly at Columbia and Northwestern Universities, as well as those of Section 7.2 of NDRC, give extensive discussions of airborne fire-control systems and of the problems encountered in evaluating them. [12, 13, 88, 90, 117]

From these agencies came such outstanding developments as the Texas sight-testing machine [14, 15, 17, 18, 86] and the "tricamera" method for the assessment of flexible gunnery. The latter was worked out jointly by the Army (Eglin Field), Navy (Patuxent) and NDRC. [73, 121] (See Section 22.3.1.)

This chapter deals with the assessment of radar fire-control systems. However, the radar portion cannot be planned or tested separately from the sighting system into which it is incorporated. Accordingly, this discussion will follow rather general lines.

22.1 SPECIAL NATURE OF ASSESSMENT OF AIRBORNE FIRE-CONTROL EQUIPMENT

22.1.1 Contrast between Airborne and Land-Based Testing

In the assessment of fire-control systems on the ground, the problem is simply that of shooting at targets similar to those encountered in combat. Comparative target scores then give an accurate measure of the relative merits of the various fire-control devices. Even when the system is mounted on a ship, it is possible to compensate adequately for the motion of the platform.

Difficulties arise when the target is airborne, but when the fire-control system itself is carried in an airplane the problem of assessment is enormously more complex. In the air one is firing from a gun platform which is in motion. This motion may be uniform or accelerated. Changes in motion may be smooth or abrupt. The changes in motion suffered during combat will depend to a considerable degree upon tactical considerations which change from time to time. The strain of combat may reduce the accuracy of the operator. The pilot will usually crowd on all possible speed during combat, while under test conditions he will fly more slowly for the sake of safety, accuracy, and airplane maintenance. Furthermore, the kinematic problem presented to the computer varies with the target motion. When a slow-flying towed target is used as a substitute for a fast, rapidly accelerating fighter airplane, the results will differ enormously. The effects of these variables will of course be different for the different situations: air-to-air or air-to-ground fire; fixed or flexible gunnery; 0.50-caliber ammunition, cannon or rocket projectiles.

For these and other reasons, the target scores obtained in firing tests may have very little relation to the results which would be obtained in combat. The possibility of a fire-control system actually performing better in combat than in firing tests is indicated by a consideration of the Applied Mathematics Panel hit probability nomogram (Figure 1).

The total system (sight, gun, tracking operator or mechanism, ranging operator or mechanism) will have two types of errors: (1) *bias error*, that is, an error inherent in the sight, of constant magnitude and direction, and (2) *dispersion* or random error, composed of gun and ammunition dispersion, tracking or aiming error and ranging error. The probability of obtaining a hit upon a target of given area in square mils depends upon the bias error and the standard deviation of the dispersion, in such a way that when the bias error is held constant, the hit probability passes through a maximum value as the dispersion increases from zero. This maximum is reached when the standard deviation of the dispersion equals the bias error.

As an example, consider a sight for which parallel and perpendicular components of the errors are equal. Suppose that there is a bias error of 10 mils in the sight mechanism. By rotating a straightedge about the 10-mil mark on the left-hand scale of Figure 1, it is seen that the hit probability is very small for low values of the standard deviation of the dispersion (e.g. 0.02 per cent when $S = 4$ mils), that it increases up to a value of $S = 10$, at which it is about 0.5 per cent, and then decreases for greater values of S.

An actual example of this was believed to have been found in the tests of the K-15 or Mark 18 gyro sight.[94] The behavior of the system using radar range information supplied by AN/APG-5 was compared with that using manual stadiametric ranging. The sight had a bias error of 16 to 23 mils. The mean deviation of the radar range data was much smaller than that of the manual ranging (19 yd compared to 115 yd in one instance). Assessment showed that the hit probability with the inaccurate manual ranging was equal to or greater than that with radar range.

In terms of the nomogram, this means that the total dispersion with radar ranging was so small that the maximum hit probability had not yet been reached, while with manual ranging the dispersion was presumably so large that the maximum had been reached or exceeded.

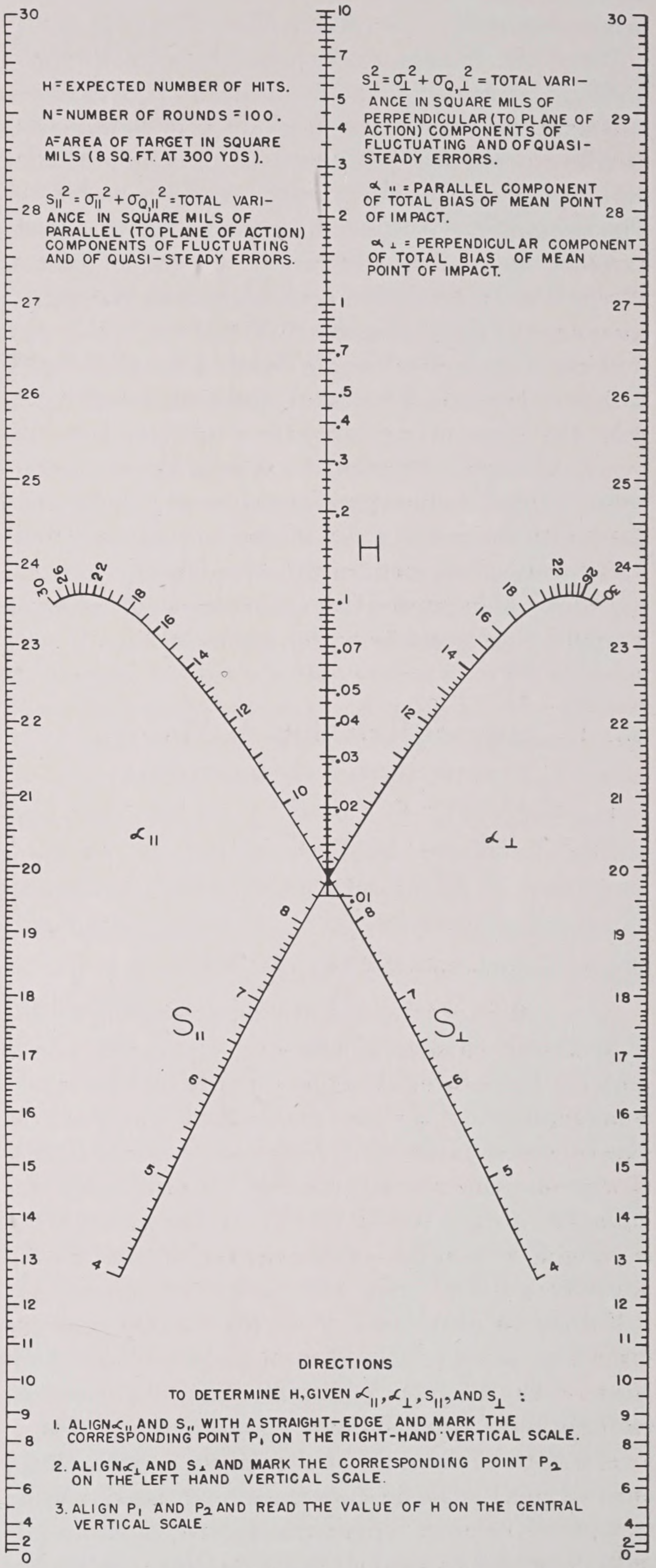
Now consider that the gunner's tracking becomes gradually worse (as it might in combat); imagine that all errors excepting tracking errors remain constant. The resulting increase in total dispersion will steadily *decrease* the hit probability with manual ranging; but with radar ranging it will cause an *increase* at first, followed eventually by a decrease. The hit probability therefore will soon become and will then always remain greater for radar than for manual ranging.

The above arguments, of course, represent an extrapolation and simplification to an extent that may not be justified in the actual case under discussion. However, they illustrate the problems which can arise, and serve to emphasize the need for coordination of effort in all phases of the development of a fire-control system.

22.1.2 Importance of Photographic Analysis

In air-to-air fire it is impossible for a test to simulate combat conditions by shooting real bullets at a real airplane. If real bullets are replaced by frangible bullets, a procedure of great usefulness in training,[85] the results are unreliable for assessment purposes because of the great difference in ballistics. The substitution of towed targets for real airplanes results in oversimplification (see Sections 22.3.1 and 22.3.2), the seriousness of which depends upon circumstances.

Even if realistic conditions could be had, there would be no way of learning whether a miss was caused by error in aim or in the sighting system. Finally, realistic shooting of any kind is statistically inefficient, in that the misses (usually a large fraction of the rounds fired) contribute little to the assessment. It is true that a radio device was under development at Laredo, Texas, which would record the



H = EXPECTED NUMBER OF HITS.

N = NUMBER OF ROUNDS = 100.

A = AREA OF TARGET IN SQUARE MILS (8 SQ. FT. AT 300 YDS).

$S_\parallel^2 = \sigma_\parallel^2 + \sigma_{Q,\parallel}^2$ = TOTAL VARIANCE IN SQUARE MILS OF PARALLEL (TO PLANE OF ACTION) COMPONENTS OF FLUCTUATING AND OF QUASI-STEADY ERRORS.

$S_\perp^2 = \sigma_\perp^2 + \sigma_{Q,\perp}^2$ = TOTAL VARIANCE IN SQUARE MILS OF PERPENDICULAR (TO PLANE OF ACTION) COMPONENTS OF FLUCTUATING AND OF QUASI-STEADY ERRORS.

$\alpha_\parallel$ = PARALLEL COMPONENT OF TOTAL BIAS OF MEAN POINT OF IMPACT.

$\alpha_\perp$ = PERPENDICULAR COMPONENT OF TOTAL BIAS OF MEAN POINT OF IMPACT.

DIRECTIONS

TO DETERMINE H, GIVEN $\alpha_\parallel$, $\alpha_\perp$, $S_\parallel$, AND $S_\perp$:

1. ALIGN $\alpha_\parallel$ AND $S_\parallel$ WITH A STRAIGHT-EDGE AND MARK THE CORRESPONDING POINT P_1 ON THE RIGHT-HAND VERTICAL SCALE.
2. ALIGN $\alpha_\perp$ AND $S_\perp$ AND MARK THE CORRESPONDING POINT P_2 ON THE LEFT HAND VERTICAL SCALE.
3. ALIGN P_1 AND P_2 AND READ THE VALUE OF H ON THE CENTRAL VERTICAL SCALE

FIGURE 1. Hit probability nomogram constructed by the Applied Mathematics Panel.

$$\text{Hit probability } H = \frac{NA}{2\pi S_\parallel S_\perp} e^{-\frac{a_\parallel^2}{2S_\parallel^2} - \frac{a_\perp^2}{2S_\perp^2}}$$

distance and direction of bullets passing a towed target, but it was not used in World War II.

When the bullets are replaced by camera shots, however, everything but the firing can be simulated, and from statistical theory the effects of the shooting can be superposed.[84] These effects include among other things ammunition dispersion and "gun climb." The nature of the latter in aerial gunnery was apparently not well understood in the earlier part of World War II. Studies of it were made by the Eighth Air Force [127] and at Laredo.[128, 129]

Recording devices are also needed for the motion of the airplane and other pertinent data. For this purpose, the camera is probably the most reliable instrument, although mechanical drum recorders were sometimes used. Temperature extremes and centrifugal accelerations such as occur in airplanes cause trouble in the usual instrument of this type. In any case, the recording of numerical data in an airplane by a human observer is highly unreliable.

22.1.3 Special Relation of Maintenance and Assessment

The remarks in this section might apply to many phases of military development, but the problems here described were accentuated by the peculiarities of airborne equipment and by the nature of radar.

Maintenance during Testing

Adequate care of a new system during the testing procedure is obviously necessary, but in practice is very hard to secure. Even first-class maintenance personnel normally do not understand the scientific basis of a new device well enough to be able to handle it without some special training. This difficulty was enhanced during World War II by the policy of assigning low priority to the needs of the testing agencies, so that there were never enough trained maintenance men to carry on the routine preflight checks, let alone to handle serious maintenance problems. Adequate test equipment and maintenance facilities were also lacking at the testing agencies.

The natural response of the development agency, such as the Radiation Laboratory, to this condition is to send its own representatives to maintain the equipment during testing. However, this practice has certain limitations, for such representatives are not typical maintenance men and erroneous impressions may be gained as to the serviceability of the equipment.

The testing agency should have first-class military maintenance personnel and equipment, and should carry out a definite program of preliminary checking on the bench, in the airplane both on the ground and in the air, as well as continued routine preflight checks. The development agency should make sure that adequate instructions for such checks are in the possession of the testing agency, and should maintain close contact with it throughout the tests.

Tests have been held up for considerable periods by such elementary difficulties as the sticking of a servo-motor, water in the antenna, or oil leaking into a cable. Occasionally a piece of equipment, such as a sight, was tested for more than twice its prescribed useful lifetime.

Failure of maintenance during the acceptance tests was one of the causes referred to in Chapter 17 for the extreme delay in the introduction of airborne radar fire-control equipment.

Assessment of Maintenance

One of the prices which may have to be paid for a new development is an increase in maintenance requirements. It is an important function of the testing agency to determine what this price is, so that policy-determining agencies will have enough information to make an intelligent decision. To this end, a complete record both of routine and of extraordinary maintenance should be kept throughout the test.

22.2 TESTS ON A RADAR FIRE-CONTROL SYSTEM — AGS

One of the systems described in this part (AN/APG-15B, Chapter 19) was tested in some detail by the Radiation Laboratory at Bedford Field. In these tests many of the major problems of assessment were well illustrated. Accordingly they will be outlined here and used as a particular example, before the more general discussion of assessment of fire-control systems. Recommendations of a general nature will, however, be included here also. A complete account of the results of these tests is given in reference 28.

22.2.1 Test Design

A thoroughly worked out program for such a test is essential. For some simple device a test program may ask only the question, "Is it serviceable?" and the test will answer yes or no. One of the mistakes encountered during World War II was the attempt to apply this oversimplified criterion to such an elaborate mechanism as a fire-control system. Of course general serviceability must be insured, but those who are planning to use the system need far more detailed information about its performance. They need it in quantitative form. They need numerical values for such quantities as the probability of securing a hit or destroying the target under definite conditions. Sufficient data must be collected so that the averages will mean something, and the data must be treated according to sound statistical methods. The Latin square method of laying out experiments should be employed where much information must be extracted from limited data.[142, 143] However, where it is possible, the collection of data should be liberal, so that statistically significant results can be obtained without extremely laborious calculation. Probable errors must be calculated, for in practice they may be just as important as the quantities themselves.

The test of the AGS system was formulated along the following lines.

Questions to be Answered

As described in Chapter 19, the AGS system provides range information to the standard B-29 computer for daytime use, and in addition, for conditions of restricted visibility provides a spot on an indicator. This spot is centered if the antenna is being aimed at the target. A thorough assessment of these functions requires answers to the following questions.

1. What is the accuracy of the range information?
2. When the gunner is tracking perfectly, that is, keeping the indicator spot centered, does the gun actually point at the target?
3. Is the distance of the spot from the center of the indicator directly proportional to the angular deviation of the target?
4. How much does the indicator spot lag behind the pointing of the antenna assembly?

Subsidiary problems were presented by the performance at very high altitude and at low altitude over water. These were not actually studied, because of the end of World War II. The second phase of the test was also designed to secure information about the performance of the gunner as affected by the functioning of the computer.

Stations and Operators Required

The equipment was installed in a TB-24 airplane, and an FM-2 was used as the target. As the location of the gunner's scope makes photography difficult, a duplicate scope was located in the waist. The gunner acted as flight supervisor, giving orders to the pilots of the two airplanes and to the camera operator. He loaded the gun camera, and of course did the actual tracking.

Another person, stationed at the second scope, was responsible for the operation of the radar and communications systems. He loaded the scope and computer cameras and adjusted the cross hairs on the scope.

The camera operator turned the cameras on and off on signal from the gunner. He filled out the report form and reported to the gunner when all was ready for a pass. He timed the use of film with a stop watch, not allowing more than 100 sec per 50-foot magazine. If more than one pass was made per magazine, he marked the division between passes by pressing down the button to operate the code marker. He was responsible for securing a boresighting shot of 50 frames with the gun camera, on the ground before each flight.

Program of Missions

Range Accuracy. Four missions, ten passes each, closing rates 25, 50, 75, and 100 mph, altitude 6,000 to 10,000 ft.

Pointing Error. Two missions, one with computer in, one with computer out, starting range 800 to 1,000 yd, five passes with target airplane doing weaving S turns, five passes with 30-degree crossover course, crossover at 400 yd.

Scope Linearity. Two missions, with different indicator-amplifiers, range 800 to 1,000 yd, target airplane flying straight and level directly behind the bomber, altitude 6,000 to 10,000 ft, measurements with sighting angles of 2, 4, and 6 degrees at 3, 6, 9, and 12 o'clock directions on the scope.

Lag between Turret and Indicator Spot. One mission, range 800 to 1,000 yd, altitude 6,000 to 10,000 ft, target airplane flying straight and level, back and forth slewing of sight at amplitudes of ±4 and ±2 degrees, and at three rates — slow, medium, and fast; medium rate corresponding approximately to average aim-wander period. Slew both in azimuth and elevation; also slewing ±30 degrees across target; also miscellaneous slewing as in typically bad tracking.

22.2.2 Instrumentation of AGS Tests

CAMERAS

Three standard GSAP cameras, N4A, 24 volts, modified to use Wollensak 17 mm lens, were used. The gun camera was provided with a 3-in. lens to give greater range accuracy, and a red filter to insure contrast. The boresighting procedure consisted of mounting a boresight telescope on the gun, pointing it at some reference object and taking about 50 frames with the gun camera. This gave the reference point from which all target angles were measured.

The computer camera photographed the range dial on the computer. The zero and slope set were to be checked before each flight. A third camera photographed the remote scope in the waist.

SYNCHRONIZING MECHANISM FOR CAMERAS

While the speed of GSAP cameras can be regulated, it is impossible to synchronize two of them perfectly; one will gain one or two frames per hundred on the other. In order to be able to match the simultaneous frames, a camera control and coding box had been developed. The switch for turning the cameras on and off was located on this box, and cables from it to the cameras provided the 24-v power for operating them. As described below, the cables also provided accurately timed pulses of electric energy which actuated the magnets that pulled out the over-run indicators, thus coding the pictures.

The mechanism for providing these pulses consisted of a speed-governed motor which operated a small gear box and thence a shaft on which a cam was mounted. This cam was in contact with a microswitch during part of each rotation of the shaft; during this time the microswitch was closed. This caused electric pulses of a fraction of a second in duration to be sent to the magnets in the cameras which in turn removed the over-run indicators. The box was also provided with a button for closing the over-run indicator circuits manually, thus allowing the indicators to remain out of the fields of the cameras continuously for any desired length of time. This form of manual code marking was used to denote the beginning or end of a run.

Just before the end of the war, a more satisfactory synchronizing mechanism was developed by the General Electric Company and modified by the Radiation Laboratory.[46] This consisted of a pair of solenoids to be inserted in the GSAP camera, which could actuate the shutter on receiving impulses from a cam-operated source at speeds up to 4 or 5 per sec. In this way perfect synchronization was obtained, without the inconvenience caused by differing camera speeds, and the magazine of film lasted much longer. When the GSAP cameras were run in normal fashion, at 16 frames per second, every fourth or fifth frame was analyzed. This solenoid drive allowed the cameras to run at exactly the desired speed. In this way a magazine of film lasted four or five times as long, thus avoiding the large waste of film, and more important, allowing longer missions to be flown in situations where reloading in the air was not possible.

TARGET AIRPLANE

Since accurate measurement of target width is essential, the FM-2 was at first provided with wing-tip lights. However, the airplane power supply proved inadequate for lights bright enough to be practical. (At Eglin Field a separate generator was used to supply lights of several thousand watts power.) Visibility up to about 1,000 yd was secured by painting black bands on the wings. These bands had to be extended all the way around the leading edge of the wing in order to be visible under all conditions. Accurate measurement of the distance between the stripes to 0.1 ft was important, as the overall accuracy of the range determination depended upon it. Four persons each measured the distance twice and the mean was taken.

Because of the great difficulty of measuring air-to-air range accurately by photographic means at ranges beyond 1,000 yd, and because of the high degree of precision shown by the radar range system, it is suggested that an airborne range-only radar set (such as AN/APG-5) be used for the measurements of target distances in future tests. It should be noted that this would be reliable with present systems only if three or four photographic checks were made in each pass at shorter ranges, and if the set were accurately calibrated, especially for the slope setting.

22.2.3 Analysis Methods

PRECAUTIONS TO INSURE ANALYZABLE DATA

It is not uncommon to find after a mission has been flown that part or all of the resulting film is useless for purposes of analysis. Probably the most important precaution is to process and view the film very quickly, so that trouble will be detected in time to avoid repetition of the error on another mission.

The GSAP camera is not a very satisfactory instrument, and must be checked frequently. Refilled magazines often stick. Before a mission the films may be marked with a pencil through the openings in the magazine, and the cameras operated very briefly to see whether the pencil marks disappear. If the over-run indicator has a dark background in the field of view it may be invisible. This should be checked with a standard camera boresight tool, and a small white card should be mounted so that the indicator can be seen clearly against it.

None of the actual operations of the mission should be left to the pilot of the airplane. He is occupied with flying and should not be required to push buttons, guess at range, or perform similar functions.

Frequent boresighting shots are necessary, as it is easy for the camera to be knocked or shaken out of alignment. Range calibration shots should be taken at various ranges, and in no case should this important function be replaced by a mere calculation from the focal lengths of the camera and projector, as camera lenses of the same specifications may differ by 10 per cent or more.

Adequate labeling of films, ordinary precautions to insure good pictures, and adequate forms for recording data are needed. It is highly desirable that the person in charge of the group which later will analyze the data should himself observe typical test missions, and a representative of this group should be present on all missions.

ERRORS IN OPTICAL RANGE DETERMINATION

The following discussion is based on a report [45] of the fire-control analysis section of the Radiation Laboratory.

The determination of the distance R from the gun to the target by optical means can be accomplished by projecting the photograph of the target on a screen, measuring the width of the image of the target and calculating the range from the formula

$$R = \frac{kT}{w}$$

where T is the actual size of the target (assuming that it is approaching head on, i.e., the aspect angle is zero), w is the measured size of the picture of the target, and k is a constant, the value of which depends upon the units employed, the focal lengths of the camera and the projector, and the distance between the projector and screen. Computation of k from these quantities, however, is difficult and inaccurate, a fact which is perhaps not widely enough appreciated. In an assessment report [81] appearing after the end of World War II, the surprising statement is made that a simple proportion gives range to an estimated accuracy of 3 per cent "regardless of the length of the range"! It is true that the context implies that maximum ranges of about 1,500 yd were being considered, but even below this limit the error is an increasing function of range. It is better to make a number of calibration shots at a series of known ranges of an object with known dimensions, obtaining a good value of k by averaging. Alternatively, the angle S subtended by the object can be measured by a surveyor's transit at the camera. Then,

$$R = \tfrac{1}{2}T \cot \frac{S}{2}$$

if R and T are in the same units.

Since

$$\frac{R}{T} = \frac{k}{w},$$

then

$$k = \frac{W}{2} \cot \frac{S}{2}$$

if R and T are in the same units. Since S is usually less than 10 degrees, cot $S/2$ can be replaced by the value of $2/S$ in radians.

The most important single error in this range determination is that involved in measuring w on the screen. Since the error in w depends upon the accuracy with which the two ends of the calipers can be placed upon the image, it will be about the same for small images as for large images. Now the width of a given target image on the screen is inversely proportional to the range. Therefore the percentage error in range, from this source, is directly proportional to the range; or the absolute error in range, expressed for example in yards, is proportional to the *square* of the range. To illustrate, suppose that the image can be read to 0.02 in. and at a range of 500 yd appears 2 in. wide. The error will be 1 per cent, or 5 yd. At 1,000 yd the image will be 1 in. wide, giving an error of $0.02/1 = 2$ per cent or 20 yd.

The other important error, that in focusing the image on the screen, seems to be proportional to w.

Table 1 shows the combination of these errors (overall percentage error) in range for different sizes of target at different ranges, assuming a measuring error of 0.02 in., a focusing error of 1 per cent, and a projection distance of 80 in.

TABLE 1. Per cent error in range. Blanks correspond to values of the subtended angle greater than the field of view of the camera lens.

Range R in yards	Target size T in feet								
	25	50	75	100	200	300	400	500	1,000
500	1.49	1.18	1.11	1.09	....	....	....	....	....
1,000	2.36	1.49	1.26	1.18	1.09	1.06	....	....	....
2,000	4.34	2.36	1.76	1.49	1.18	1.11	1.09	1.08	....
3,000	6.41	3.33	2.36	1.90	1.32	1.18	1.13	1.10	....
4,000	8.50	4.34	3.00	2.36	1.49	1.26	1.18	1.14	1.08
5,000	10.59	5.38	3.67	2.85	1.69	1.37	1.24	1.18	1.09
6,000	12.70	6.41	4.34	3.33	1.90	1.49	1.32	1.23	1.10

By considering this table one sees that for accurate measurement of ranges greater than 1,000 yd, it is desirable to have a target divided into measured portions (such as a bridge or a long building with definite divisions between sections), so that several portions can be measured at long ranges, and one portion at short ranges. However in air-to-air tests this is impossible, so that a practical limitation of about 1,000 yd is imposed upon photographic ranging. Radar ranging is, however, good to far greater distances.

An error in range will be produced if the line from the camera to the target is not perpendicular to the measured line in the target, that is, if the aspect angle is not zero. If the angle is known, a correction can be made, which is negligible for angles up to 5 degrees. With larger aspect angles, such as are encountered in assessing fighter gunnery, a small uncertainty in aspect angle will produce a considerable error in the range. Further discussion of this point, and tables of errors, are given in the report cited.[45]

SOME RESULTS OF AGS TESTS [28]

Some samples of the range accuracy measurements are given here to illustrate the kind of accuracy which was obtainable. Figure 2 shows typical photographs of the target airplane which were used for photographic range determination. Figure 3 gives sample curves comparing radar range with photographic range at four different closing rates. Figure 4 shows such a comparison in one of the early runs of the test, and is given to show how bad the results can be if improper attention is given to the various precautions. For example, the distance between the stripes on the target airplane had been measured only once, and there was some uncertainty about the calibration of the radar set; other details also had not been standardized.

Throughout the test, after the correct procedure had been established, the radar range agreed with the photographic range well within the probable error of the latter.

Figure 5 shows the results of one of the tests of the lag of the spot indication behind the turret. In this test the radar system had a time constant of 0.1 sec, while under the usual operating conditions a value of 0.25 sec was used.

The term time constant as used here refers to the time constant of the chief portion of the circuit as calculated from the resistance and capacity ($k = CR$; k will be expressed in seconds if C is in microfarads and R in megohms).

If a linear differential equation of the form

$$k\frac{d\lambda}{dt} + \lambda = 0$$

governs the displacement λ of the spot on the scope, then $\lambda = \lambda_0 e^{-t/k}$; and k will be the time required for the spot to move a fraction $1 - 1/e$ of the distance which the target moves in a sudden displacement from rest.

If the target is moving back and forth with respect to the radar antenna in some periodic fashion, for example as a sine function, then

$$k\frac{d\lambda}{dt} + \lambda = \sin \omega t$$

and

$$\lambda = (1 + k^2\omega^2)^{-\frac{1}{2}} \sin(\omega t - \tan^{-1}k\omega) + ce^{-t/k}$$

The time lag k' of the spot is seen to be $\tan^{-1} k\omega/\omega$, which is less than k.[28]

Referring to Figure 5, where $k = 0.1$ sec, it is seen by comparing the peaks of the two curves that k' is about 0.13 sec. With $k = 0.25$ sec, k' is found to be 0.3 sec or greater. The fact that these time lags are greater rather than less than the time constant calculated from the circuits shows that a linear differential equation of the type discussed is only a rough approximation. Greater time lags than these can be tolerated before the tracking system becomes unstable in the hands of a gunner.

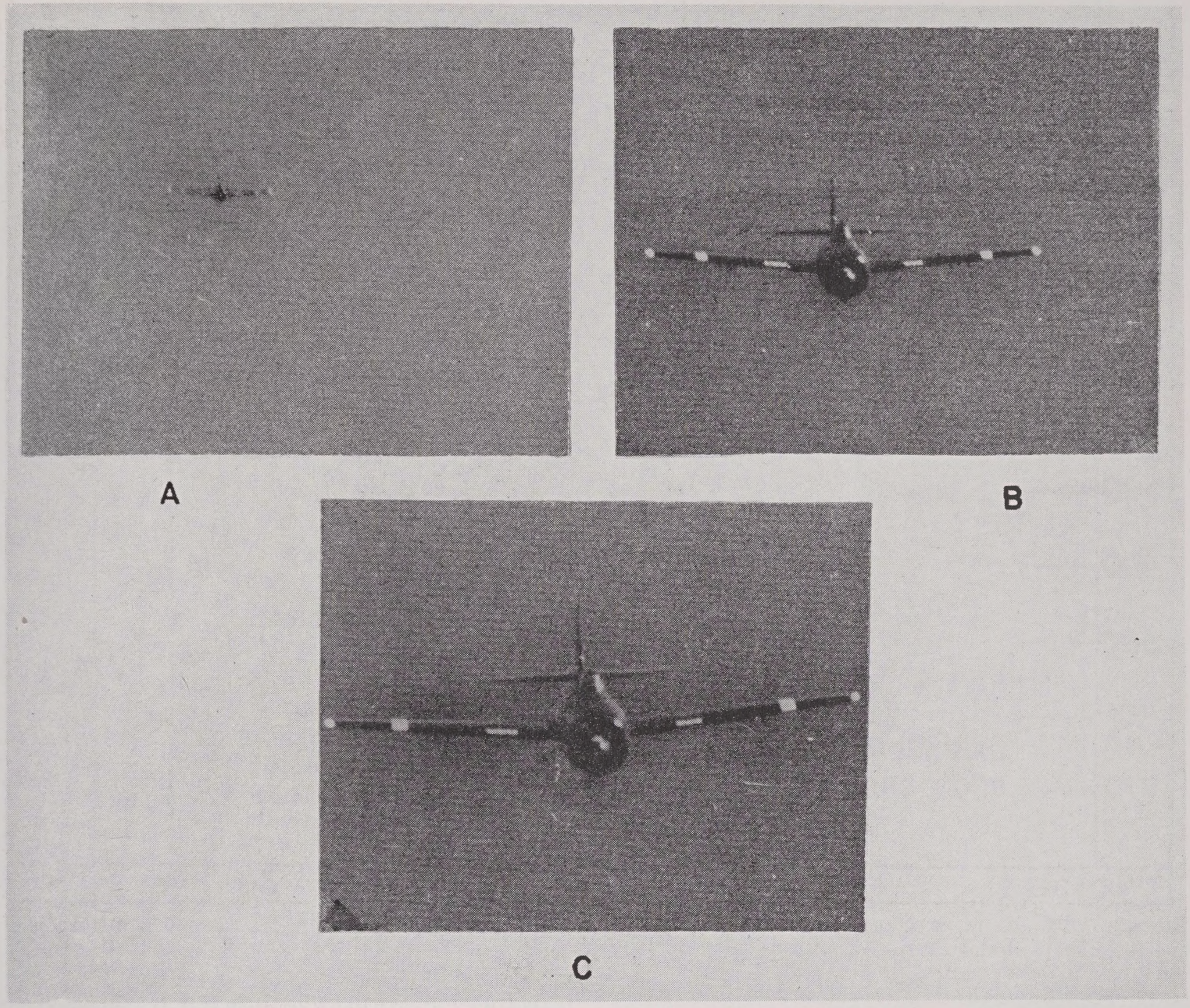


FIGURE 2. A. Target airplane at 1,060 yd. B. Target airplane at 270 yd. C. Target airplane at 200 yd.

22.3 ASSESSMENT OF FIRE–CONTROL SYSTEMS

The preceding discussion is based upon the direct experience of the analysis group at the Radiation Laboratory. This group also took part in or followed many other tests of fire-control systems. The following discussion is based upon these observations. More detailed accounts will be found in the reports of the Applied Mathematics Panel, NDRC Section 7.2, the AAF Proving Ground at Eglin Field (usually issued as AAF Board reports), the Navy testing agencies at Patuxent (Naval Air Station, Bureau of Aeronautics) and Inyokern (Naval Ordnance Test Station, Bureau of Ordnance), as well as other Army and Navy testing agencies.[12–15, 17, 18, 62, 84, 86, 88, 90, 92, 96, 116]

Airborne fire-control systems fall into three groups: control of flexible gunnery, as used in the turrets of bombers (and to a limited extent in night fighters); control of fixed gunnery in fighters; and air-to-ground fire control for cannon and rockets. This chapter will not deal with the analytical assessment of sights, that is, the separate calculation of the errors which would be shown by a mechanically perfect sight perfectly operated.[62, 96]

22.3.1 Assessment of Bomber Fire-Control Systems

The purpose of this assessment is to determine the effectiveness of the system in shooting down or driving off attacking fighters.

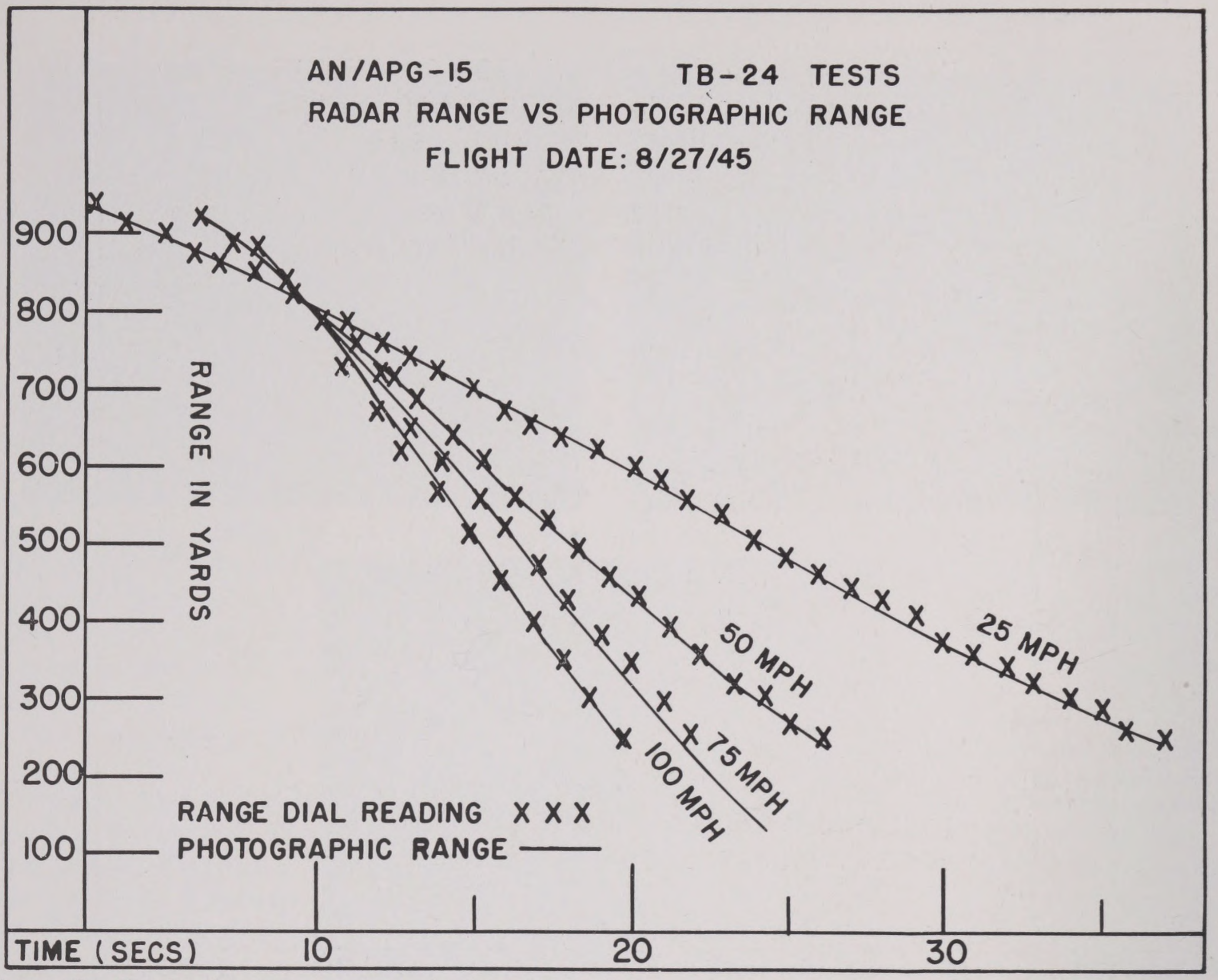


Figure 3. Graphs of radar range determined by AN/APG-15 as compared with range determined photographically at four different closing rates.

Towed Targets and Drones

Towed targets have been used to test the fire of bomber turrets, but the results of these tests have little value, for the behavior of the targets is very different from that of attacking fighters.

A better approximation to fighter aircraft is given by drones, i.e., remotely controlled small-scale airplanes. Extensive testing with these is, however, extremely expensive for the relatively small amount of information which they provide.

Photographic Methods

Camera assessment of flexible gunnery has proven to be the most satisfactory method because, everything considered, it is the most realistic. It allows the use of real fighter airplanes as targets and it records the fate of all of the bullets that would be fired in an attack, rather than only those few that hit the target. A comparison of camera tests against a towed target with firing tests against the same towed target was made at Eglin Field and a close correlation of scores was found.[121]

In all types of photographic assessment a camera is mounted with its axis parallel to the gun bore and wired so that in a simulated attack the camera operates when the trigger is pressed. These gun-camera photographs, properly calibrated, show the angle by which the gun is leading the target. An evaluation of the lead which should have been used [58] requires a knowledge of the course of the target airplane. This in turn requires a stable frame of reference with respect to which the motion of the target can be measured. A method of photographing the target against a background of clouds or mountains was developed at the University of New Mexico.[93, 94, 119] It is useful for rapid assessment, but the so-called tricamera method and the closely related deflectometer method [60, 73, 82–84, 91, 99, 100, 106, 118, 121] used at

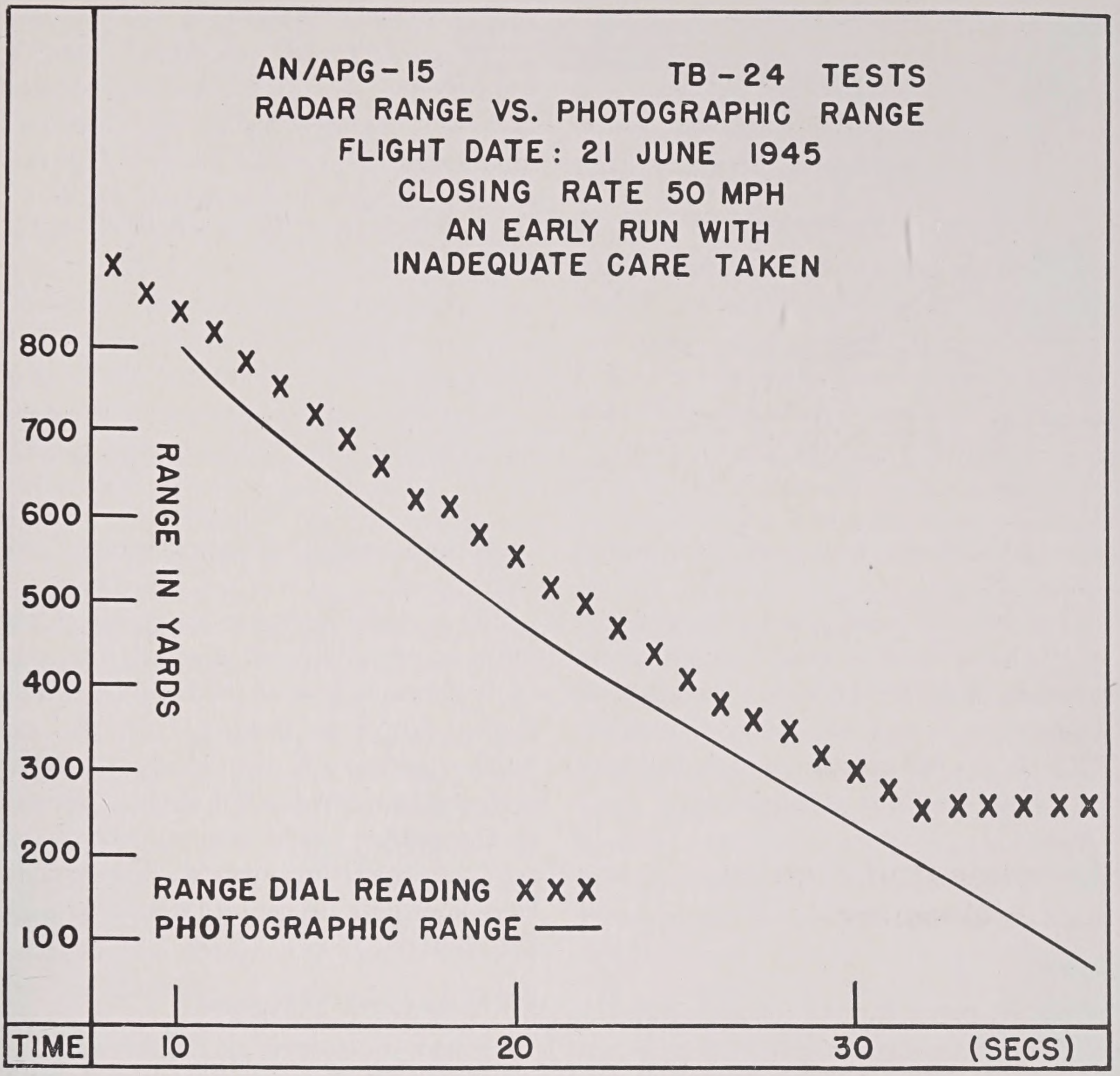


FIGURE 4. Graph of radar range obtained under poor operating conditions.

Eglin Field and Patuxent, while requiring slow and painstaking work, are capable of higher accuracy. In the former, a group of three cameras, the tricamera, mounted rigidly together, photographs the complete field of vision to one side of the bomber, and includes a wing tip and the tip of the stabilizer fin in the photographs. If the bomber is flying absolutely straight and level, the successive pictures of the target in this field give the necessary data; but if the bomber is subject to motion about its longitudinal, lateral or vertical axis (roll, pitch, or yaw, respectively) then the apparent motions will be in error. These motions can be compensated by a calculation based upon a knowledge of the amount of roll, pitch, and yaw, which in turn can be obtained from synchronous photographs of an attitude gyro. The deflectometer is an instrument which measures the position of the gun in the bomber frame of reference by recording the turret position. This is done by photographing either the turret machinery itself, or dials operated remotely by selsyn motors.

A valuable sight assessing machine was developed at the University of Texas [12–15, 17, 18] by means of which an operator in the laboratory can track the projected image of an airplane with an actual sight, the path of this image being determined by a cam which in turn is made to duplicate an actual combat course. The operator's platform can be made to undergo roll and yaw. From the photographic records obtained by this machine, it is possible to compare the lead put in by the sight with the correct lead, either assuming perfect ranging or assuming some form of incorrect ranging as supplied by a cam, or allowing stadiametric ranging by the operator. The advantage of this machine is that it computes the gun pointing errors very accurately and quickly. It seems probable that an increasing amount of confidence will be placed in it, although the test is less

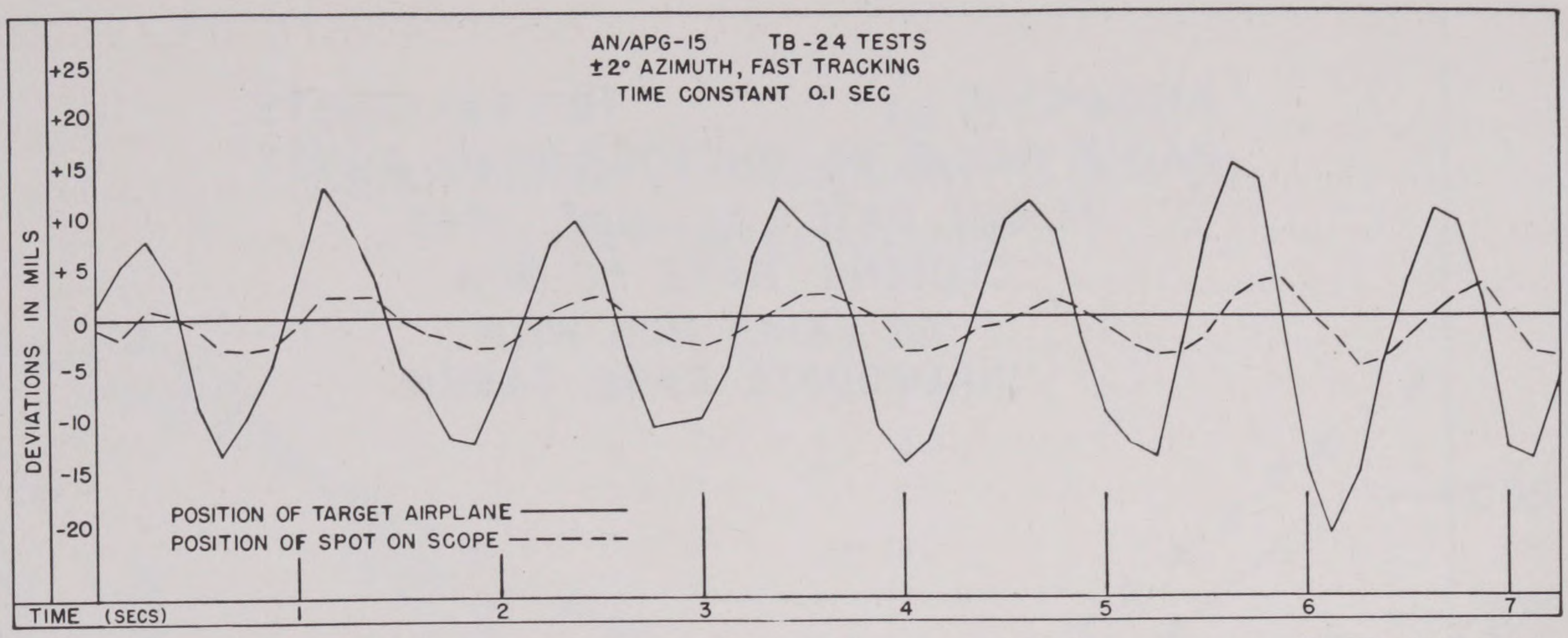


FIGURE 5. Comparison of position of target airplane with spot on radar scope, as the sighting system is slewed periodically.

realistic than the camera assessment in actual flight.

For the sake of completeness, two ideas should be mentioned which have been proposed as still more accurate assessment methods. These are the air-mass coordinate method,[11, 115] and the photometeoronic method.[88, 130] The latter has attained a high degree of precision in other applications at Aberdeen.

22.3.2 Assessment of Fighter Gunnery

Towed Targets

The use of towed panel targets for assessing the performance of a fighter fire-control system is not objectionable in principle (although here also the shots which miss serve very little purpose), for the towed target can be made to approximate the motion of a bomber reasonably well, except for speed. The following difficulties were encountered in World War II. Although these are small in themselves, any of them can cause the test to break down.

1. If the fire-control system is good, many targets will be shot away and lost unless a multiple line (similar to parachute shrouding) is used.
2. The small size and nonreflecting character of the panel target as compared to a bomber requires that a corner reflector be inserted in it if radar ranging or tracking is used. Even optical ranging presents a minor difficulty, as the standard reticle is too large.
3. Rounds fired against lost targets must be subtracted in calculating scores.
4. Fighter pilots may be very far off in their estimates of range, e.g., 300 yd called 1,000 yd, so that some instrumental (camera or radar) record of range is needed when the shooting accuracy of a system is being measured in different range "blocks" or regions.

For a really accurate appraisal of the system in terms of probability of effective hits, a knowledge of the vulnerable area of the bomber at different aspect angles would be needed.[113] In the assessment of bomber gunnery it was assumed that the vulnerable area of a fighter was a 5-ft circle. This was reasonable, as the fighter would normally be flying almost directly toward the bomber. However, it is unlikely that a similar procedure would be satisfactory for the bomber.

Photographic Methods

Camera assessment of fighter sights is less highly developed at present than that of bombers, and special difficulties present themselves because of the more complex motions of the gun platform in space and because of the pattern of gun fire. Two of these motions are "mush" (the effect of the angle of attack of the fixed gun, which varies with speed and curvature of the path), and "skid" or side-slip. The former can be measured roughly and taken into account. The latter can be detected (although not always by the usual indicator), and those runs discarded in which it is present (see Section 22.3.3).

The basic problem in this assessment can be stated in terms of the photograph of the target bomber taken by the fighter gun camera. Assuming that the center is the boresight point, then the point must be found where the bullet will be when it has traveled a distance equal to the range (strictly, future range). This requires an estimate of range, gravity drop, mushing, and skid effects. This point must then be compared with the point where the bomber will be at that time. The motion of the bomber therefore must be known. Three methods have been proposed for finding this. The one which was developed the furthest was that of photographing the fighter from the target bomber. This was used at Patuxent.[81] Another method, involving only films taken from the fighter, was developed at Eglin Field. In it, a plastic disk with a pin passing through the center was mounted upon a movable pedestal. The pin represented the bomber. By rotating this model until its shadow coincided suitably with the projected image of the bomber on a screen one could determine azimuth and elevation of the bomber, angle off and range. This method was a refinement of the W-2 fighter-sight assessor for training fighter gunners, used at Foster Field.[125] By the end of the war no publication on it had appeared from Eglin Field, and its potential accuracy had not been determined, although one well-trained operator was able to reproduce his readings on angle off to within 1 degree.

A third device was designed by S. Eilenberg and J. H. Lewis,[105] based upon a proposal of R. Hayward, Mount Wilson Observatory. It is similar in principle to the W-2 method but uses a small luminescent model which is compared with the film by a viewer directly, instead of using projection on a screen.

From the information obtained by one or more of these methods the direction of flight of the bomber is determined, the kinematic lead is calculated and measured off on the photograph and the spot thus found is compared with the calculated location of the bullet.

22.3.3 Assessment of Air-to-Ground Fire-Control Systems

The two preceding sections dealt largely with 0.50-caliber fire. In air-to-ground combat this is used only for close-range strafing; fire-control problems here are concerned with airborne cannon and rocket fire, where the use of radar increases the practical range up to 6,000 yd, as discussed in Chapter 20.[72, 121]

In the assessment of range accuracy it was possible to make use of the principle of a target composed of measured sections (Section 22.2.3, "Photographic Methods"), so that reasonable photographic range accuracy was obtained at 6,000 yd. The most effective sectional target was one at Dugway, Utah, consisting of a square array of roads, 2,000 yd on a side, with parallel crossroads at 200-yd intervals. The aiming point was a corner reflector located at a road junction. Photographs at long range showed ten 200-yd segments, and at the end of a run showed only one segment. Analysis of these films was carried out rapidly and accurately, and without much of the usual strain on the analysts.

Wind and Target Motion

Air-to-ground fire-control systems in use at the end of the war made provision neither for motion of the target on the ground, nor for wind. It was found in the 75-mm cannon tests that the lateral component of the wind was easily corrected for by the pilot, who chose an aiming point to the right or left of the true target. The component of the wind or target motion in the direction of the flight path was harder for the pilot to judge and nullify. Further developments should take care of this problem if high precision at long ranges is desired.

The Effect of Skid in Rocket Fire

Tests on the use of radar range systems in air-to-ground rocket fire at long range had been commenced but a factor which is of minor importance with cannon fire here became a serious problem. This is the problem created by the skidding or side-slipping of the airplane; the rocket launcher points in a direction different from that in which the airplane is moving. The seriousness of this problem arises from the fact that a fin-stabilized rocket, unlike a shell, leaves the launcher practically in the direction in which the airplane is moving rather than in the direction in which the launcher is pointed (that is, it heads into the relative wind). In actual tests it is observed that occasional rockets go very far to the side of the target.

There are two conventional means by which skid has been estimated. One is the feeling in the seat of the pilot's pants, the other is a bubble, free to move in a curved tube of liquid. It is known, however, that under some conditions a skid of fairly sizable amount (2 degrees) will escape detection by both of these means.[87, 107]

Some devices were under development at the end of the war which would detect skid, and others which would correct it. The former were much more nearly perfected than the latter. The "Barber Pole" of the Specialties Company is an example. A yaw head with two openings is mounted on a wing of the airplane. Rubber tubes lead from these to a cylinder with helical stripes, mounted horizontally within the pilot's field of vision. When a pressure differential exists between the openings, the cylinder is caused to rotate in the direction of skid, attracting the pilot's attention. While this does not give the amount of skid, it does allow the pilot to correct for it as soon as it begins. A sensitivity of 2 mils is attainable. However, this would be too sensitive for practical use, and damping would be required.

22.4 GENERAL PHILOSOPHY OF ASSESSMENT

The concept of a test as a single, simple occurrence to answer the question, "Do we want it?" has long since been outmoded. The modern view regards testing as a process that goes on continually, from the first experimental model, through the development stages, the small scale application stage and does not stop even when large scale application is reached. The success of characteristic American peacetime engineering accomplishments is partly owed to this process. The surprising backwardness of German radar development is credited to the fact that the scientists who invented the equipment had no contact with it after it left their hands, a situation which was apparently true in many cases with the manufacturers as well. The desire for military security was allowed to stifle the free exchange of ideas secured in experimental use, by which the designers and manufacturers could have made the rapid advances which characterized British and American military technology.

22.4.1 Need for Experimental and Engineering Testing

In spite of the admirable way in which practical experience was frequently made available for the scientific workers who were engaged in the development of new devices, fire control was not improved as it might have been. The philosophy of the acceptance test, pure and simple, delayed matters. A fire-control system would be developed in the laboratory, tested out with the limited facilities available to the development agency, which usually did not include ranges where firing was possible, and then sent to the testing agency where, for the first time, firing tests were conducted. The natural failings of a new system, and the lack of training of the testing personnel would result in an unfavorable test report. This might hold up matters for a number of months, or, if someone in high authority had faith in the system, it would be placed in production in spite of the adverse opinion. Toward the end of the war a more efficient attitude was adopted, for instance at Eglin Field, where a distinction was made between engineering tests and final acceptance tests, and some systems were given the experimental or engineering type of test while in the small-scale manufacturing stage, then modified in such manner as the test results showed necessary. The value of direct experience to the scientist or engineer working on a system is great enough to suggest that a few such persons should be trained to fly fighter aircraft. There seems to be a disagreement among authorities as to whether this is feasible or not.

22.4.2 Limitations of Testing Methods

However thorough the engineering and acceptance testing may be, it cannot give all of the information needed to make an intelligent decision about the usefulness of the system in actual combat. Operations to be performed by human operators have been shown to be much less accurate under combat conditions than under test conditions. Test pilots become familiar with the terrain of their own ranges; they may be affected by prejudices for or against the equipment; they will probably fly at lower speeds than they would under combat conditions. Errors that compensate one another under test conditions may not compensate in combat, and vice versa. Maintenance crews may be less careful about fire-control equipment under test than when they know that their lives may depend upon its being in the best possible condition.

22.4.3 Combat Trials

The above considerations lead to the idea that testing under combat conditions would be desirable. Whether this is possible depends upon circumstances.

CONTRAST BETWEEN OFFENSIVE AND DEFENSIVE TESTS

It is clear that any system to be used in offensive combat can be given a test at almost any desired time, unless the enemy has collapsed. On the other hand, it may be unwise to introduce new offensive equipment in the development stage because its possible loss over enemy territory would compromise the development. Defensive equipment cannot always be subjected to the same ready testing. For example the AN/APG-5 system with the K-15 sight was installed in a few bomber turrets in the Mediterranean theater, and flown on combat missions, but it never received any real trial as the German fighters did not attack.

Use of Small, Specially Equipped Groups

Ideally a small combat test group would be organized as soon as practicable, given special training in the operation and maintenance of the system, and sent to a theater of operations. Trained observers would accompany the group with facilities for photography and other means of securing test data, and the results of such observations would be utilized by the development agency as rapidly as possible in the further improvement of the equipment. Needless to say, a decision on the overall acceptability of the system could not await such a test, for the time lag would be too great.

[redacted]

PART V

AIRBORNE MOVING TARGET INDICATORS

Chapter 23

BASIC PRINCIPLES OF AMTI

23.1 INTRODUCTION

One of the most important radar implements of a modern tactical air command is an airborne device capable of detecting moving vehicles of all descriptions at night or during periods of poor visibility. For example, the lack of such a device cost the Allied forces tremendous losses in the Battle of the Bulge, because they were not fully prepared for the vast forces that crept in against them under cover of the ten-day period of foggy weather during which the normal type of aerial reconnaissance was impossible. The usual type of airborne search radar does not provide a means for distinguishing moving vehicles from ordinary ground clutter because it works on the basic principle of target contrast.

The pulse doppler phenomenon, however, does provide a means for distinguishing between moving vehicles and ground clutter. The basic principles of detection depend upon the fact that the relative motion, with respect to the radar transmitter in the aircraft, is different for fixed ground targets than for moving targets.[2–4] In particular, an airplane flying over the land receives echoes from the the ground with frequencies shifted slightly from the transmitter frequency because of the relative motion of the ground and the aircraft. The doppler frequency shift is approximately 30 c at X band for a radial velocity of 1 mph. Thus, for an airplane velocity of 200 mph the shift is approximately 6,000 c for echoes fore and aft and 0 for echoes abeam. If the vehicle on the ground has a radial component of velocity toward the airplane, there will be an additional shift of frequency corresponding to the total radial components of velocity of airplane and vehicle. For example, if the vehicle has a radial velocity toward the aircraft of 20 mph and lies ahead of the aircraft, the total shift of frequency will be approximately 6,600 c. Normally the frequency shift is not detected by the radar in the aircraft because it is negligible compared with the bandwidth of the receiver. However, if the returning signal is allowed to beat with an oscillator whose frequency is the same as that of the transmitter, this beat-note can be detected and its frequency will correspond to the velocity of the vehicle with respect to the aircraft. If the frequency of the oscillator is equal to that of the transmitter plus the doppler frequency shift corresponding to the motion of the aircraft over the ground, then the beat-note frequency will correspond to the velocity of the vehicle with respect to the ground.

23.2 THEORY

23.2.1 Doppler Principle for Moving Vehicle Detection

The doppler frequency shift [2, 3] at the transmitter-receiver caused by the relative radial velocity, V, of the target is approximately

$$f = \frac{2V}{\lambda}$$

$$f = 29.8 \text{ cycles/sec/mph at } \lambda = 3 \text{ cm.} \qquad (1)$$

The shift may be detected by beating the echo together with an oscillator whose frequency is the same, or nearly the same, as the frequency of the transmitter, and in other related ways discussed in what follows.

Continuous-Wave Transmission Method

The simplest application of the doppler principle to a detection device for moving vehicles is that in which a *continuous-wave* [CW] transmitter with its antenna is set up adjacent to the receiver and its antenna.[4] The echo returning from the target, as well as some direct energy from the transmitter, enters the receiver and the ensuing beat-note indicates target motion. Although this is a very sensitive method for detecting moving targets, it does not give their ranges nor does it discriminate among them except in azimuth (then only by virtue of the antenna pattern). It is not readily applicable as an airborne moving vehicle detector because of the difficulty of separating the indications coming from the ground from those coming from the moving vehicle.

Noncoherent Pulsed-Transmission Doppler Method

In order to obtain the range of the target in addition to its azimuth, it is convenient to resort to a pulsed system such as an ordinary radar.[25, 29] When the airborne radar is used over land, the frequency of the echoes returning from the random fixed scatterers on the ground is shifted from the transmitter frequency according to the relation given above;

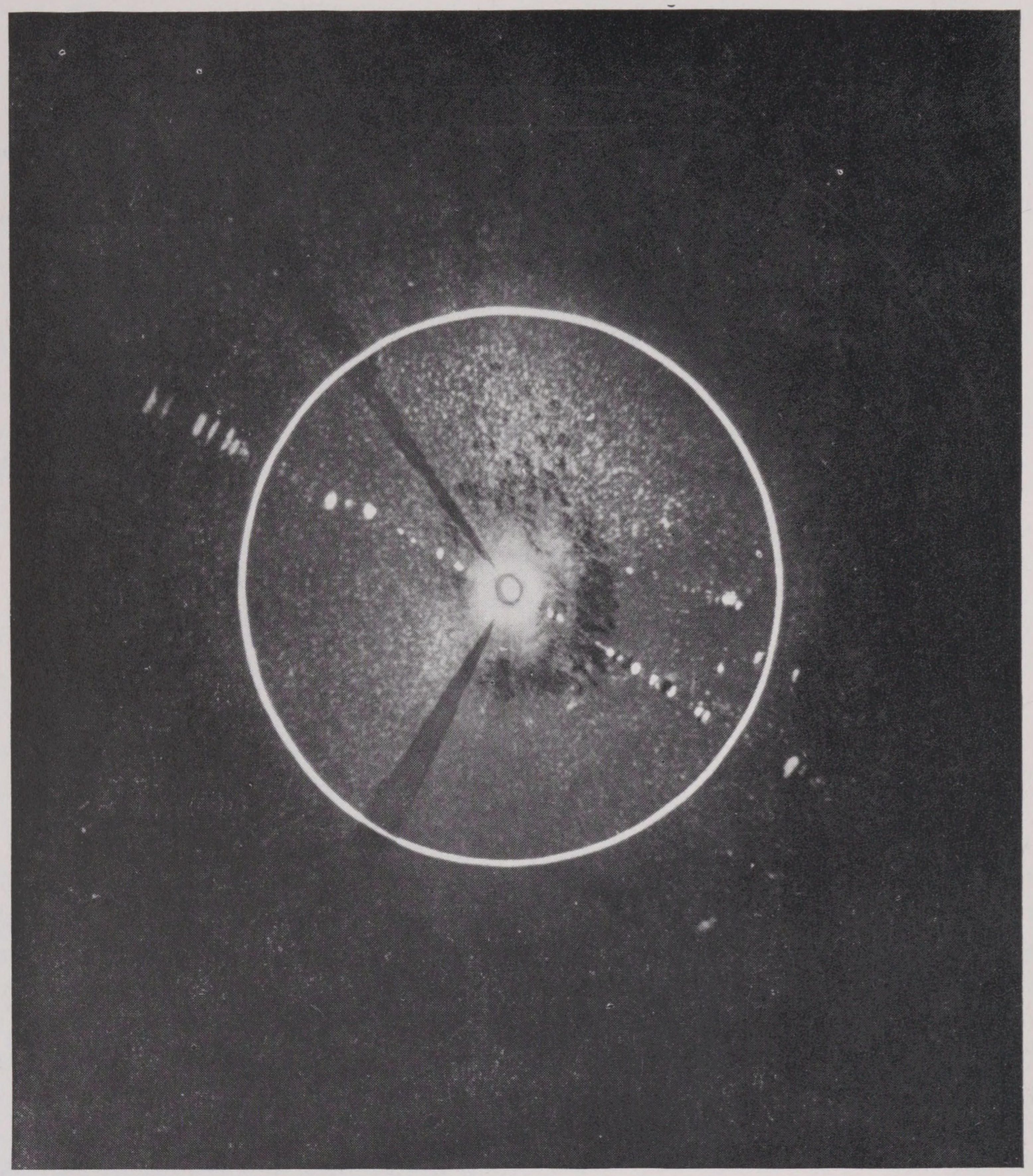


FIGURE 1. Photograph of the cathode-ray tube in the Firefly (AN/APS-27) moving vehicle detector, showing a line of moving vehicles on the Newburyport Turnpike, and a few isolated moving vehicles. The range circle is at 5 miles radius.

and, as mentioned in the introduction, the shift cannot be detected by the ordinary radar receiver. If a moving vehicle lies within the field of view of the radar the situation is different; the returning energy is the vector sum of the energy of the scatterers near the vehicle and the energy from the vehicle itself; as the vehicle moves toward or away from the aircraft, the phase of its echoes changes with respect to the phase of the echoes from the background by 180 degrees for every quarter wavelength or 0.3-in. radial motion of the vehicle (at X band) and the echo energy from the vehicle alternately adds and subtracts from the average energy of the region. The periodic amplitude modulation or flutter of echoes so often seen on the A scope is evidence of the motion of the target with respect to its background (slow fluctuations of a few cycles per second are usually due to frequency shift of the transmitter or inhomogeneities in the refractive index of the air). The frequency of the beat-note modulation is given by the relation $f = 2V/\lambda$, where V is now the radial component of the velocity of the vehicle with respect to the ground.

The term noncoherent doppler detection is given to the above phenomenon because no coherence or established phase relationship is required between the oscillations from the transmitter and from the echo. The phenomenon has the property that the motion of the aircraft relative to the ground does not result in modulation of background echoes except as a secondary effect; only targets moving with respect to the ground show the modulation. Consequently, it is possible to detect vehicles at all azimuth angles provided that they have sufficient radial velocity with respect to the instantaneous position of the aircraft. An illustration of noncoherent doppler moving vehicle detection is shown in Figure 1.

In addition to the modulation frequencies caused by the presence of moving vehicles, there will also be some modulation frequencies because of the finite width of the beam. These modulation frequencies will be present in the return from random fixed scatterers because of the differential radial velocities. The case for scatterers located at a given range and at the half-power points of the beam is illustrated in Figure 2.

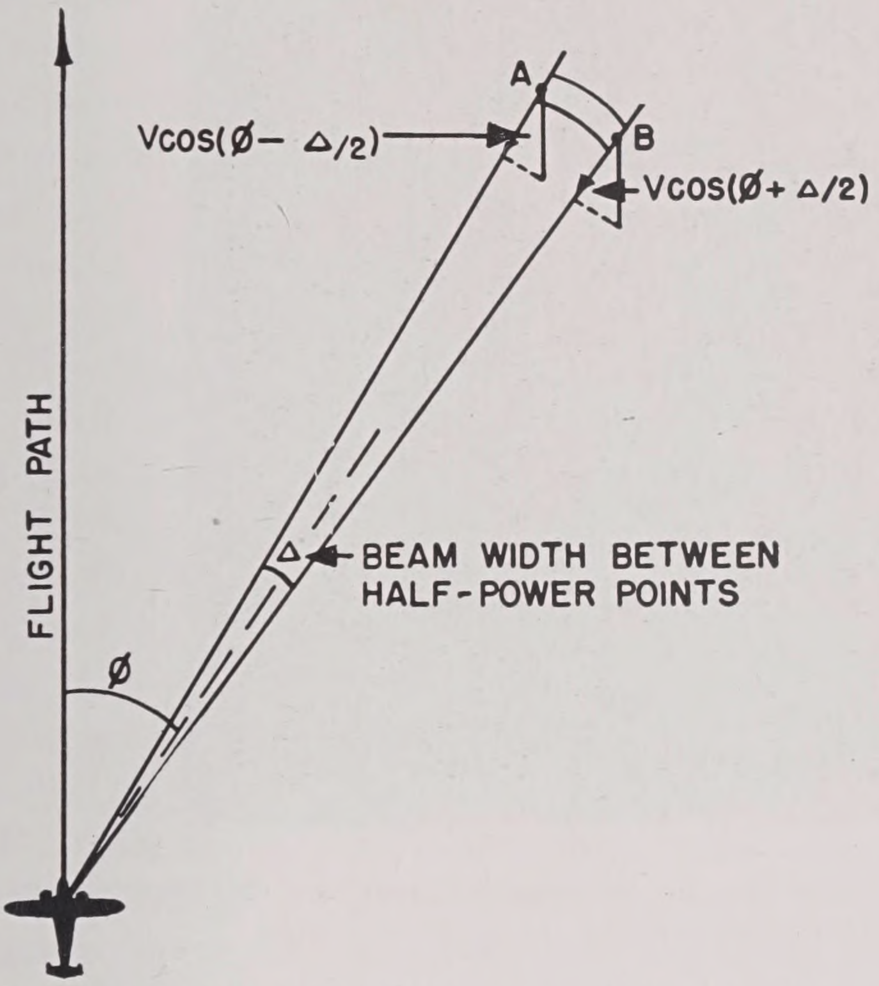


FIGURE 2. Noise modulation caused by finite beamwidth. The modulation is minimum for $\phi = 0$ or 180 degrees and maximum at $\phi = 90$ or 270 degrees.

The radial component of velocity of a scatterer at point A is

$$V_1 = V \cos\left(\phi - \frac{\Delta}{2}\right),$$

at point B

$$V_2 = V \cos\left(\phi + \frac{\Delta}{2}\right),$$

and

$$V_1 - V_2 = 2V \sin\phi \sin\frac{\Delta}{2}. \tag{2}$$

The corresponding modulation frequency is

$$f = \frac{4V}{\lambda} \sin\phi \sin\frac{\Delta}{2} \tag{3}$$

which is maximum when $\phi = 90$ or 270 degrees (i.e. abeam). In the case of a 3-cm radar with 29-inch parabola, $\Delta \cong 3° \cong 1/20$ radian, and for $V = 200$ mph, $f_{\max} \cong 300$ c (equivalent to 10 mph). In practice, beamwidth modulation results in a spectrum of frequencies from 0 up to several hundred cycles per second and appears as noise on the A scope, rendering it somewhat more difficult to detect moving vehicles abeam than fore or aft. A *plan position indicator* [PPI] photograph showing "wings" due to beamwidth noise is shown in Figure 3.

In taking full account of beamwidth effects it is also necessary to consider differential radial velocities existing in range between the fixed scatterers at a given azimuth angle. An expression somewhat similar to the above may be derived for beamwidth modulation as a function of tilt-angle of the beam, indicating that at close ranges and steep angles the noise frequency spectrum is of the same order of magnitude as that noted above.

In the case of the pulsed radar system, the doppler frequency must be different from the *pulse recurrence frequency* [PRF] in order to be detected. They will be equal when the target moves exactly one-half a wavelength toward the aircraft between pulses, in which case there will be no change in relative phase between target and background echoes and no energy modulation will occur. Similarly, the target will be undetectable when the modulation frequency is an integral multiple of the PRF. In general, blind speed regions are given by

$$V_{\text{blind}} = \frac{n \cdot \text{PRF} \cdot \lambda}{2} = n \cdot 67 \text{ mph} \tag{4}$$

where $n = 1, 2, 3, \cdots$ at $\lambda = 3$ cm, PRF 2,000.

Thus for a system of the above characteristics, blind speeds will occur in the regions of 67, 134, 201 mph (see Figure 4). Although theoretically it is impossible to detect vehicles whose velocities lie within the blind speed regions, it is still true that fluctuations in the speed of the vehicle, in the disposition of the random scatterers in the background, and mutual interference between various reflecting surfaces of the vehicle itself will, for all practical purposes, eliminate the blind speed regions.

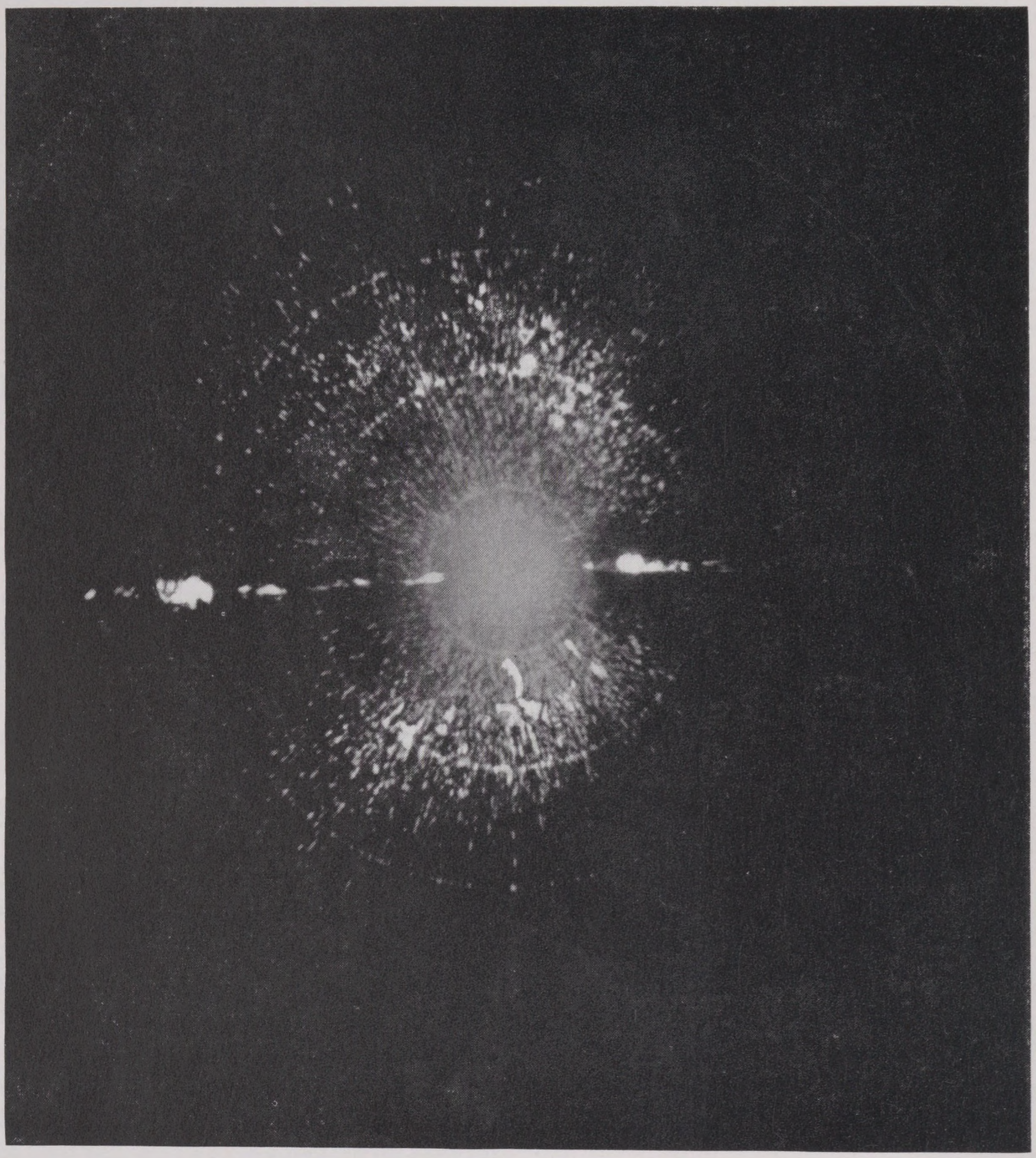


FIGURE 3. Firefly scope. One-mile range marks. Moving vehicles on the Worcester Turnpike. Noncancellation "wings" caused by beamwidth modulation noise show that noncancellation effects are greatest abeam.

COHERENT PULSED-TRANSMISSION DOPPLER METHOD

The fundamental difference between the noncoherent and coherent methods [4,39] lies in the location of the source of oscillations with which the moving target echo is mixed to produce the beat-note.[2,3] In the coherent pulsed doppler system the source is a CW *coherent oscillator* [COHO] in the radar itself. Use is made of the fact that each pulse which returns from the echo bears a definite phase relationship with respect to the transmitted pulse. The COHO provides the means for measuring this phase relationship. This oscillator can either drive the transmitter which is then a power amplifier or be driven by, or in phase with, the transmitter. At microwave frequencies the most successful coherent pulsed doppler system to date has used a CW coherent oscillator which is driven by the magnetron in the following way. The r-f transmitter pulse, at 2,970 mc, is mixed with 3,000 mc r-f energy from a very stable local oscillator to form a pulsed beat-note at the intermediate frequency (30 mc). This pulse is then used to start up as well as to control the starting phase of a 30-mc oscillator which feeds into an i-f mixing channel in the receiver. The starting phase of the 30-mc oscillator (the COHO) will depend upon the relative

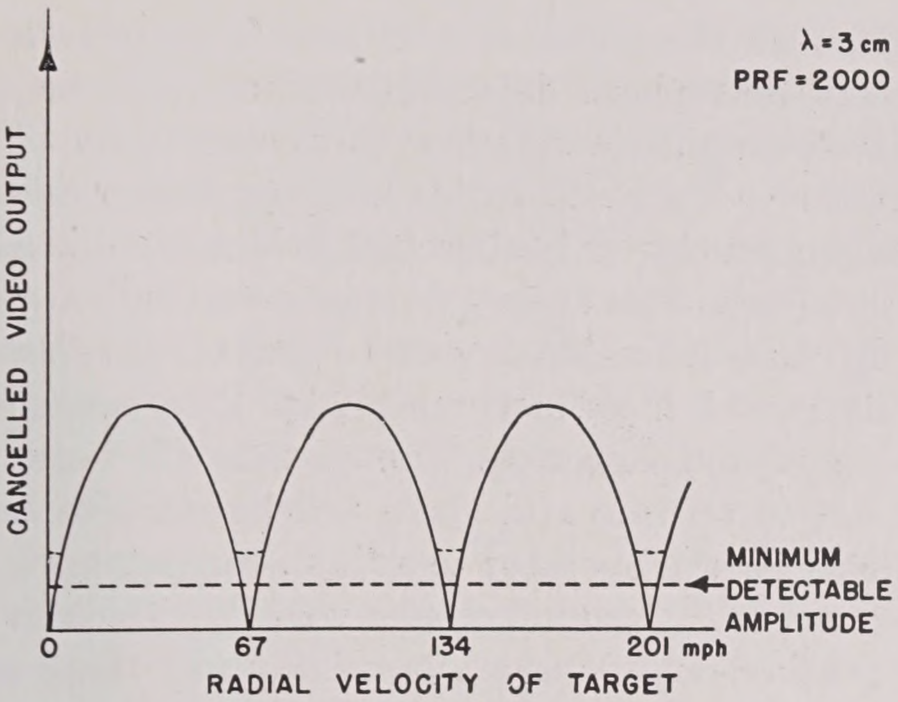


FIGURE 4. Receiver output versus radial velocity of target. The "blind speed regions" are at 67, 134, 201, etc., mph.

phases of the transmitter and the *stable local oscillator* [STALO]; if they are initially in phase, the starting phase of the COHO will be at maximum amplitude; if they are 180 degrees out of phase, it will be 0, etc. In any case, the coherent oscillator will bear a definite phase relationship to the *combined* phases of transmitter and stable local oscillator at the instant of initiation of the transmitter pulse.

The return echo at 2,970 mc beats with the same stable local oscillator to produce a 30-mc beat-note (i-f) whose starting phase depends upon the combined phases of the echo and the stable local oscillator. From pulse to pulse, this starting phase will vary from 0 to 360 degrees, depending upon the phase of the stable local oscillator. At the same time, the starting phase of the coherent oscillator will have passed through identical phase shifts, with the net effect that *the phases between the coherent oscillator and echo beat-note bear a fixed relationship to one another* from pulse to pulse. Their phases relative to the transmitter pulse may vary from 0 to 360 degrees, but their phase difference will not vary from pulse to pulse. When the i-f and the 30-mc coherent oscillations are mixed in the detector circuit of the receiver, they will add or subtract and the signals will appear on the A scope as either up or down, but will not vary in fixed amplitude from pulse to pulse.

If the vehicle producing the echo is in motion, the phase relationship will not remain fixed from pulse to pulse, and the signals on the A scope will show amplitude modulation of frequency $f = 2V/\lambda$, spreading out, both up and down. This fact distinguishes the moving from the fixed targets and permits their echoes to be separated by methods to be described in Section 23.2.2.

In an airborne coherent pulsed doppler system all fixed scatterers on the ground except those abeam show motion and consequent amplitude modulation of frequency [23,28]

$$f_\theta = \frac{2V_g}{\lambda}\cos\theta\,, \tag{5}$$

where θ is the azimuth angle the beam makes with the direction of flight and V_g is the ground speed of the aircraft. All the echo pulses in the entire "string" of pulses are identically shifted in phase with respect to the coherent oscillator from pulse to pulse because of the motion. The phase shift corresponds to f_θ. Consequently, if the phase of the coherent oscillator is shifted a similar amount from pulse to pulse, the phases between coherent oscillator and the individual beat-notes will again bear a *fixed* relationship to one another, and the deflections on the A scope will again stay constant, up or down, except for moving targets. The coherent oscillator phase shift is accomplished by adding to the coherent oscillator frequency an *audio* frequency corresponding to f_θ so as to produce a new coherent oscillator frequency of 30 mc + f_θ. Thus the effective starting phase of the coherent oscillator will be the sum of the three phases of transmitter, stable local oscillator, and *audio-frequency phase shifter*. The phase shifter computing box is tied in with the azimuth gearing of the radar scanner so as to produce the proper variation of f_θ with azimuth angle. A manual adjustment is provided for setting f_θ to the appropriate value for reducing the general clutter modulation to a minimum.

The coherent pulsed doppler system has the advantage over the noncoherent system in that it is possible to detect moving vehicles, aircraft, and ships in the absence as well as in the presence of ground clutter. Furthermore, as explained in the next section, the phase detection device is inherently superior to an amplitude detection one because phase fluctuations in extended ground clutter, caused either by scanning or by wind, are independent of the size of the clutter.[42] Therefore, the clutter produces a uniform residue which can be set up equal to noise. The sensitivity to a target moving through the clutter is independent of the phase of the clutter.

23.2.2 Cancellation and Presentation

The object of the noncoherent and coherent systems outlined above is to produce video (or i-f) echo signals which are amplitude-modulated from pulse to pulse for moving targets and fixed in amplitude for stationary ones. The simplest form of presentation of this information is the A scope on which the stationary target signals stand up or down while the moving ones have the appearance of a butterfly.

By gating the video a modulated echo can be isolated from the others in time. The modulation can be detected in a pair of headphones. By passing the gated echo through suitable pulse-stretching and clamping circuits, the recurrence frequency can be almost completely eliminated leaving only the audio modulation signal. This is the principle of the *Butterfly* system (AN/APS-26) [29] to be described later. In the *Firefly* system (AN/APS-27) [25] and *airborne moving target indicator* [AMTI] system for Cadillac,[28] the modulation on the echoes is detected by sending the radar video signals down a mercury delay line or into a storage tube which stores them for a period of one recurrence cycle and compares them in amplitude with the string of echoes from the next pulse. The result of this operation is to cancel out all those echoes which are relatively unchanged in amplitude from pulse to pulse and let through those that differ in amplitude from pulse to pulse. These residual signals are then displayed on the plan position indicator of the radar in the normal manner.

A word of warning is introduced here for those contemplating using a noncoherent pulsed doppler system for bombing purposes where accurate target range is required. The range of the leading edge of the cancelled video from a moving target echo depends not only upon the range of the target but also upon the range of the dominating clutter echoes adjacent to the target. As a result, some uncertainty and fluctuation will be introduced into the range measurements. The effect bears investigation in problems where range measurements more accurate than one pulse width (400 ft) are required.

23.2.3 Limits of Detectability

The output amplitude of the cancelled video is a function of the velocity of the vehicle and the receiver characteristics. Theoretically, the amplitude drops to zero in the blind speed regions as shown in Figure 4.

The ability of the system to discriminate between moving targets and background clutter is a complex function of the properties of the clutter itself (magnitude and phase), characteristics of the receiver, cancellation unit, presentation, and precision of adjustment of the temporal and amplitude cancellation.

Although the question is debatable, at present it appears that phase detection methods will be superior to amplitude detection (noncoherent doppler) methods [2, 3, 31] for separating moving target echoes from ground clutter background, which is subject to large amplitude and phase fluctuations. On the other hand, phase detection has the disadvantage that it requires much more instrumentation than noncoherent amplitude detection. The system will be more difficult to operate and there will be more manual controls for the operator to adjust. Furthermore, at close ranges the ground clutter velocity, which must be cancelled out, changes appreciably with range and the velocity computer box becomes unduly complicated.

Theory indicates that the sensitivity of the phase detection scheme utilizing pulse-wise comparison is such that owing to spurious changes caused by noise, equipment instability, ground-clutter fading, and scanning, moving targets which are more than about 25 db weaker [3] than the underlying ground echoes cannot be detected by methods operable at acceptable scanning speeds. Experimental verification of this figure has not yet been obtained.

Minimum detectable speeds and minimum separation of vehicles for resolvable signals have been determined for only one system to date, namely Butterfly. Vehicles traveling at 4 mph have given satisfactory indications. Targets 250 ft apart were separable as individual signals on the A scope. In ground tests a single man walking at about 2½ or 3 mph was readily detected and the rhythmic fluctuation of the tone corresponding to each individual footstep was easily discernible.

23.3 SYSTEM DESIGN CONSIDERATIONS

23.3.1 The Radar System

Any imperfection in the radar itself that shows up as modulation of the video signals will reduce the overall sensitivity of detection of weak signals. In the radar, hum due to pickup can be eliminated by operating certain of the tube filaments (especially those in the receiver) on the aircraft's d-c supply, and hum due to incomplete filtering of the power supplies can be eliminated by additional filters. In high-powered radars the additional filtering imposes a serious space and weight burden. An alternative method whereby the *effects* of the hum on the output can be eliminated without actually eliminating the hum itself is to synchronize the recurrence frequency of the radar to the power supply frequency (400 or 800 c) or to twice the power frequency (800 or 1,600 c) so that each transmitted pulse occurs at the same point on the a-c cycle. This scheme requires either that the storage device be independent of the recurrence interval, for example, a storage tube of some type, or that the a-c frequency be regulated within narrow limits. The latter has not yet been achieved in practice.

Triggering and circuit jitter is another serious source of modulation. Spark gap modulators cannot be used. The transmitter jitter must be kept less than 0.02 μsec for satisfactory cancellation.

In scanning systems the antenna is designed to provide a fan or cosecant-squared beam pattern in the vertical plane so as to produce adequate ground illumination, and in the horizontal plane as narrow a pattern as possible in order to maintain a good signal-to-clutter ratio.[14] The sensitivity of the system is a function of the scanning rate, beamwidth, type of storage device, and other variables. For example, in pulse-to-pulse comparison, a high scanning rate together with a narrow beam will result in loss of sensitivity because of the shift in beam between pulses, with resulting partial noncancellation of fixed echoes. Frame-to-frame comparison devices,[6, 10] such as mosaic storage tubes, permit a high scanning rate, but the excessive time interval between looks renders them impractical for airborne systems.

The selections of the transmitter wavelength λ and its PRF determine to a large extent the operational characteristics of the system. The PRF establishes the maximum possible range. By reference to Figure 4 it may be seen that λ and the PRF establish the blind speed regions and the minimum detectable vehicle speed. The λ and antenna diameter determine the beamwidth and hence the beamwidth modulation. For X band, a reasonable compromise between the positions of the blind speed regions, beamwidth modulation, and minimum detectable speed (about 4 mph) was arrived at by making the PRF 1,600 c. A minimum detectable speed of less than 4 mph (doppler frequency, 120 c at X band) is probably undesirable for an airborne system because of beamwidth, modulation, clutter fluctuations, and a-c hum.

A receiver of considerable dynamic range (40 to 60 db) is necessary if good discrimination between weak signals and clutter is to be attained over a wide range of clutter signal strength.[26, 27] Modulation obviously cannot be detected if the ground clutter signals saturate the receiver intermediate frequency. Theoretically, the best type of receiver appears to be one having a linear characteristic at low input levels and a logarithmic characteristic thereafter. This subject is still open to question.[8, 26]

23.3.2 The Cancellation Unit

Although considerable work has been done on delay-line and storage tube types of cancellation units, much more development is required before either type can be properly evaluated. It is possible to exclude from this discussion the mosaic-screen framewise cancellation device because with present scanning rates, the losses in frame-by-frame comparison are prohibitive.[10] Pulse-wise storage devices are divisible into two classes: those that require precisely controlled recurrence frequency (delay-line type) and those that store the string of video pulses for an indefinite period (storage tubes).

DELAY-LINE TYPE

The design of the delay line [9, 12, 15, 16, 18, 19, 21, 22, 25, 27, 33, 34] is intimately bound up with the problem of accurately controlling the recurrence interval of the pulses so that the video signals emerging from the cancellation unit are superimposed exactly on the video signals from the succeeding pulse. Two general schemes have been employed in airborne equipment for automatically or semiautomatically maintaining the proper recurrence rate.

One scheme [28] employs a separate delay line, slightly shorter than the video delay line, as a time element in a regenerative trigger circuit. The total time delay in sending a triggering pulse down the short line, through the amplifiers and a blocking oscillator to initiate the succeeding triggering pulse, is made exactly equal to the time delay interposed by the video delay line. The modulator is triggered by the timing circuit; time delays in the modulator trigger are unimportant provided they are constant because they result in delaying successive strings of video pulses by identical amounts. Another form [25] of this same scheme is a 3-crystal delay line in which a separate pick-off crystal inserted slightly ahead (0.1 μsec) of the video pick-off crystal provides the proper time delay for the timing circuit.

The other scheme involves using a simple 2-crystal delay line [25] for timing as well as for the video delay. The triggering pulses in the timing loop are generated by a free-running phase shift audio oscillator whose frequency can be controlled to within 0.004 per cent by the voltage developed in a tracking and coincidence circuit. This arrangement can be adjusted to provide completely automatic temporal cancellation thereby relieving the radar operator of one of his many duties.

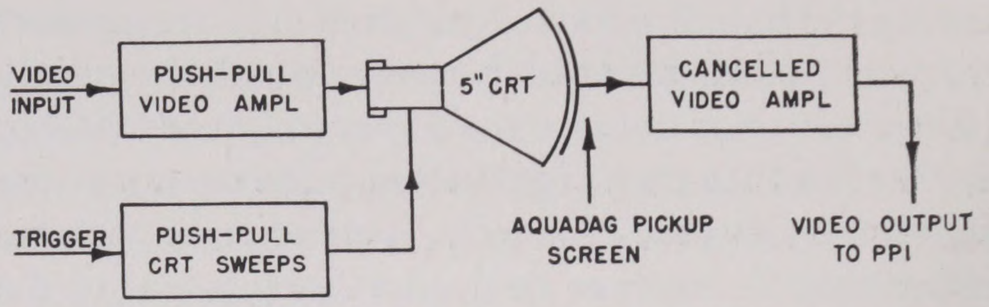


FIGURE 5. Cancellation by an A-scope storage tube.

Storage Tube Type

A deflection-modulated 5-inch cathode-ray tube[25] operated in a manner similar to an ordinary A scope has been employed successfully as a storage device. Video signals from the radar are applied to the deflection plates of the tube in the usual manner. The signals are taken from a capacity pickup screen attached to the external face of the tube as shown in Figure 5. This arrangement has the surprising property that only differential signals due to amplitude modulation of the radar signals are picked up, amplified, and transmitted on to the PPI. At present, the phenomenon is not completely understood. The fact is that as long as the beam accurately retraces its path, no sudden change in charge appears on the pickup screen, but when the beam deviates from its previous path, corresponding to a fluctuation in amplitude of the signal, then a pulse is observed at that time. The great advantage of the storage tube is that it permits the PRF to be synchronized with the power supply. It would also permit the PRF to be varied or staggered so that blind speed regions could be eliminated.

Additional information on subjects closely related to airborne moving vehicle detectors is contained in references listed in the bibliography for Part V.

Chapter 24

AIRBORNE MOVING TARGET INDICATOR SYSTEMS

24.1 BUTTERFLY (AN/APS-26) (AUDIO PRESENTATION)

24.1.1 General Description

From the technical standpoint, the simplest airborne moving vehicle detector is the *Butterfly* system (AN/APS-26) [29] which detects by the noncoherent pulsed doppler method and presents the information as an audio tone in the radar operator's headphones. In operation, the radar beam is merely pointed in the direction of flight of the aircraft, and the range gate (about 500 ft wide) is set to a point approximately 2 to 3 miles ahead of the aircraft. Only those moving vehicles in the narrow strip approximately 3,000 ft wide and 500 ft in range produce beat-tones in the headphones. As the aircraft flies along its course, vehicles lying within the 3,000-ft swath are intercepted, one by one, and they produce in the headphones short musical tones from 1 to 2 sec duration. The pitch of the tone indicates the radial component of the velocity of the vehicle relative to the ground, and an experienced operator can make inferences about the type of vehicle by the character of the note; tanks, trucks, and similar vehicles will produce strong low-pitched signals; jeeps and faster moving vehicles, higher-pitched ones. Some typical indications are shown in Figure 1.

From the tactical standpoint, Butterfly is somewhat limited in usefulness. An aircraft carrying the equipment must be under a close control system, for example, the SCR-584/M with MC-627 plotting equipment, so that it can be directed precisely enough over roadways, railroads, or waterways to assure that they lie within the 3,000-ft strip. At first sight, this limitation may appear to be a staggering disadvantage, but when the entire tactical picture is visualized, it will be seen that close control of the aircraft is desirable in any case. In an operational mission the operator radios back to the control station when he "hears" the vehicles, and the plotters at the station then mark the location of the vehicles on the map. Knowing the position of the vehicles to within a few hundred yards, their approximate number (convoy or individual vehicles) and roughly their type, the tactical planning section is in a good position to act immediately and send ground-controlled bombers or strafers to the region, or to plan a future attack upon the depot, dump, marshalling yards, or other concentrations as indicated by the influx or efflux of the traffic.

The tests of Butterfly under close control of an SCR-584/M and plotting board at the AAF testing ground, Eglin Field, Florida, showed that even with a preliminary low-power model of the Butterfly having a narrow beam and limited range, close control down roadways with adequate precision to keep the beam on the road was tactically feasible.

24.1.2 Technical Description

The Butterfly system is essentially a very simple radar consisting of the components shown in Figure 2. A brief description of the components of the Radiation Laboratory prototype follows.

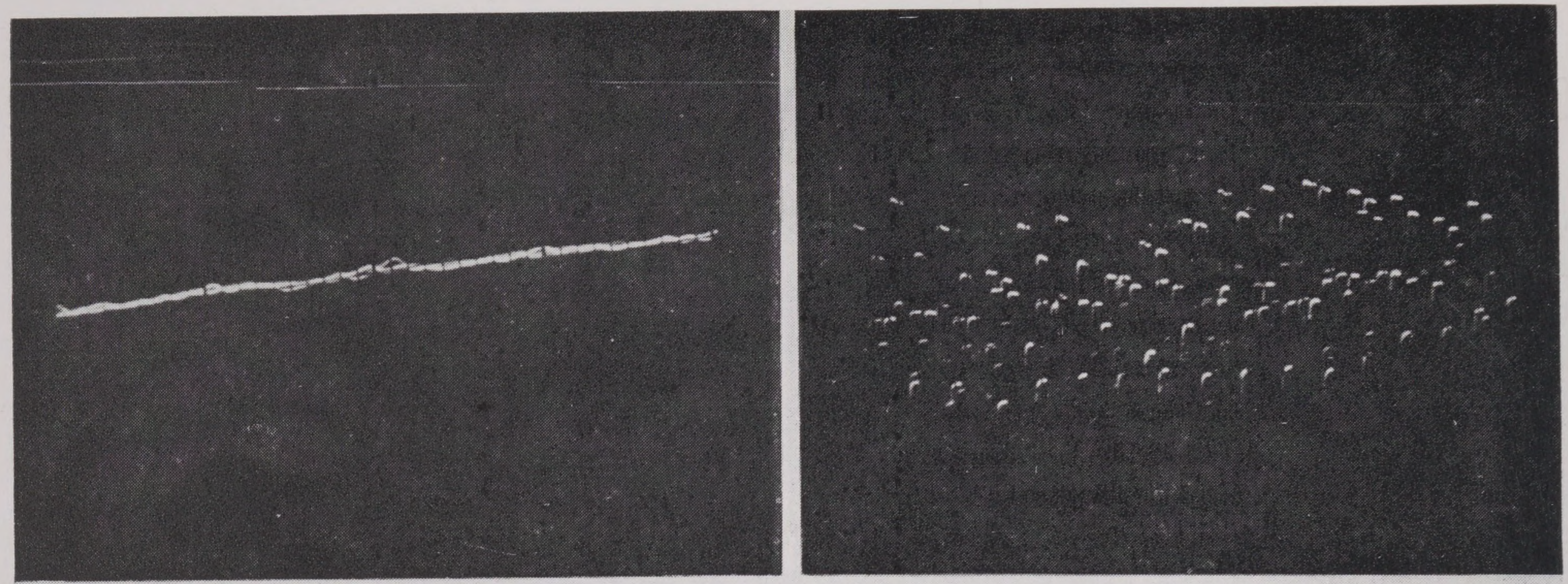
Radar

The transmitter-receiver is an AN/APS-15A modulator, modified by the addition of an extra *resistance-capacity* [RC] filter across the local oscillator voltage supply.

The antenna consists of a standard AN/APS-15A base and X band plumbing and an AN/APA-46 servo control unit for precise positioning in azimuth. The standard antenna feed is supplanted by a new one which gives a beamwidth of 9 degrees in azimuth and 3 degrees in elevation. The parabola is blocked off with "harp" (absorbing) material along the vertical side in order to attain this pattern. Tests show that the 9-degree beam introduces no serious beamwidth modulation noise, and simplifies the problem of keeping the beam on the roadway during turns and banks of the aircraft.

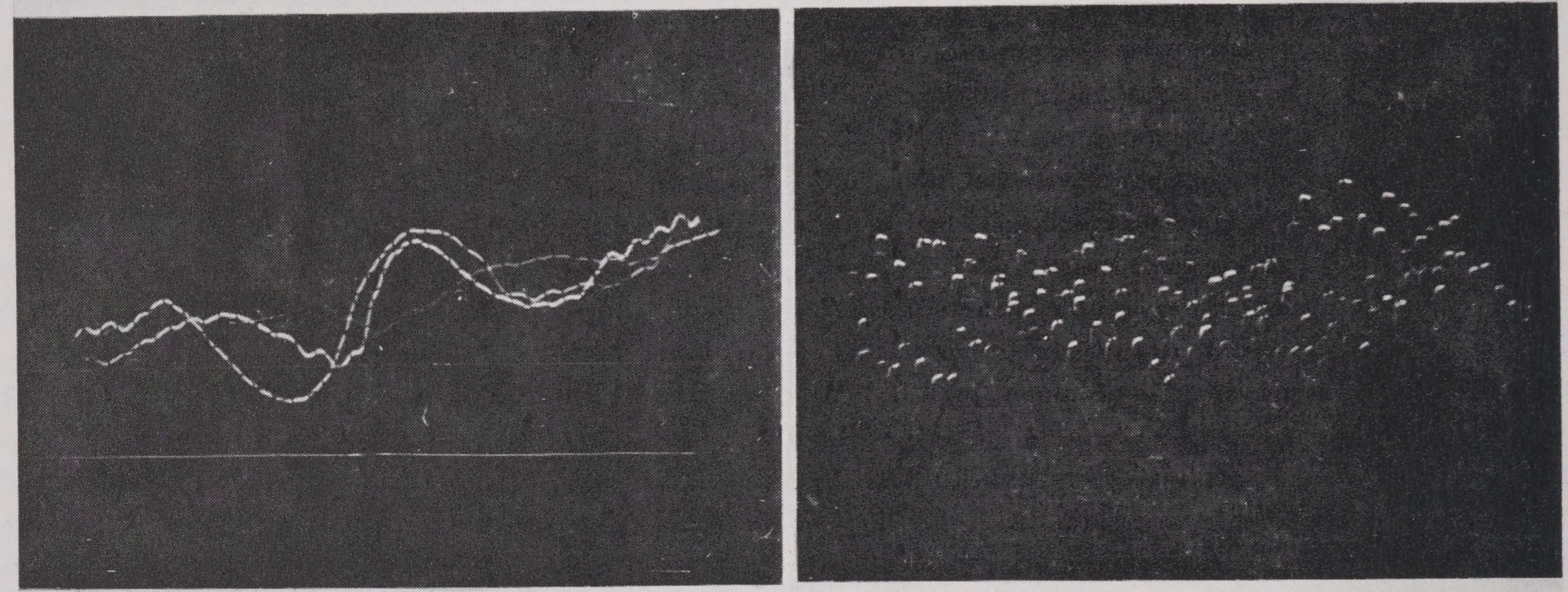
The receiver is an AN/APS-10 model modified by the addition of automatic gain control derived from the gated output signal. Its function is to keep the signal level below saturation so as to preserve pulse-to-pulse amplitude modulation.

The power supply is an 800-1-C, 115-v, 800-c converter. It establishes the *pulse recurrence frequency* [PRF] of the system at 1,600 c. As explained in Chapter 23, synchronizing the PRF with the power-supply frequency in this manner eliminates the *effect* of insufficient filtering, a-c pickup, and other factors by firing the modulator each time at exactly the same point on the a-c wave.



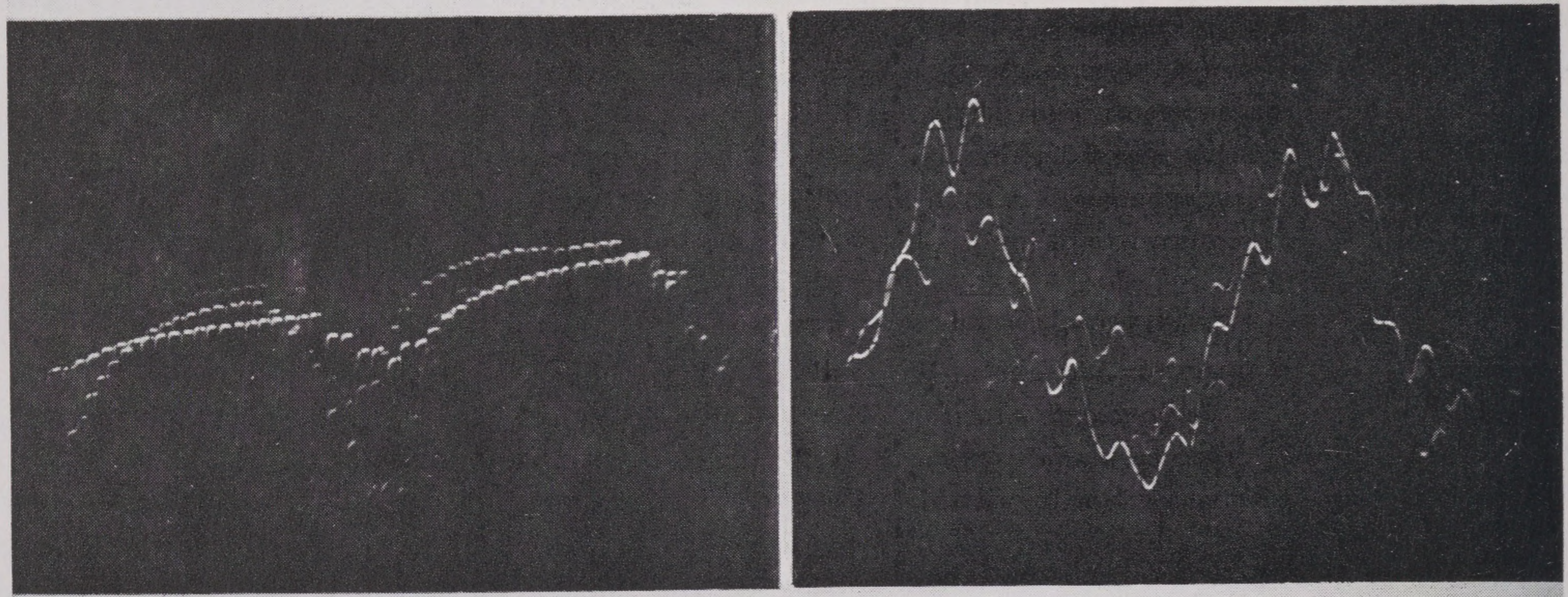
A NO SIGNAL

B CAR



C MAN WALKING

D CAR (SMOOTHED OUTPUT)



E WOMAN WALKING

F MAN AND CAR (SMOOTHED OUTPUT)

FIGURE 1. Characteristic signals from moving targets, as detected by Butterfly (AN/APS-27), measured at the audio amplifier output.

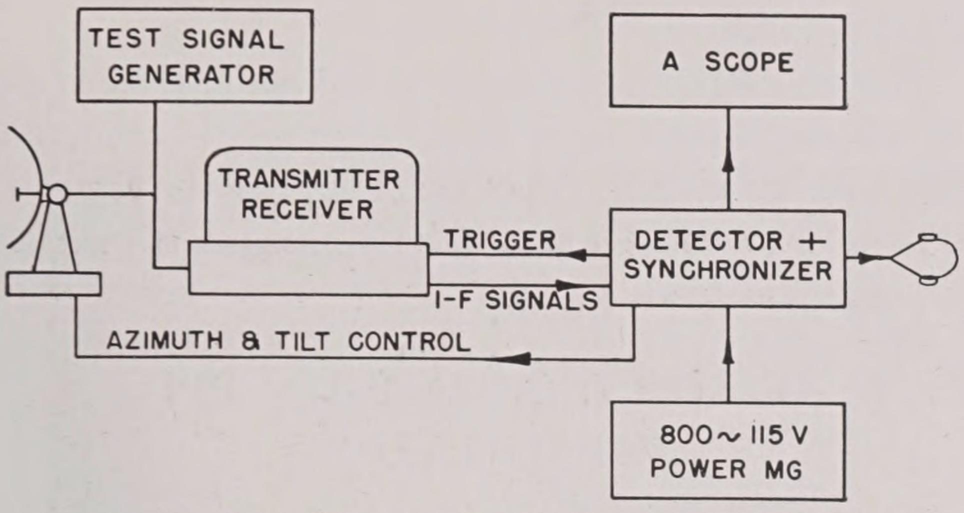

TEST SIGNAL GENERATOR
A SCOPE
TRANSMITTER RECEIVER
TRIGGER
DETECTOR + SYNCHRONIZER
I-F SIGNALS
AZIMUTH & TILT CONTROL
800∼ 115 V POWER MG

Figure 2. Butterfly (AN/APS-26) moving vehicle detector. Simplified schematic block diagram.

Synchronizing and Triggering

A simplified block diagram of the synchronizer and trigger unit is shown in Figure 3. Video from the AN/APS-10 receiver strip passes through a 1-μsec gate whose position relative to the transmitted pulse is varied by a potentiometer in the variable delay circuit. Usually the gate is set to a point corresponding to 2 or 3 miles ahead of the aircraft. After passing through the gate, the video pulses from the echo are stretched out by a clamping circuit so as to produce the envelope of the peaks of the pulses. This audio wave is amplified and passes into the headphones.

Presentation

In addition to the Butterfly signals, information from the aircraft intercommunication system passes into the radar operator's headphones so that he can hear the pilot or the radio simultaneously for liaison or warning purposes. The operator also has an A scope for visual presentation of the ungated video signals. The scope has a delayed fast sweep (6,000 yd) and a slow sweep (24,000 yd). The slow sweep is used for positioning the antenna along the direction of flight by means of the *Nosmo* (AN/APA-46) null-doppler technique, and for adjusting the antenna tilt so that the center of the beam strikes the ground at the position of the range gate. The fast sweep is used in conjunction with the headphones to aid the detection of the moving targets which are easily distinguished from ground clutter by their "butterfly" appearance.

Operation

Aside from the usual power switches, tuning and gain controls, the radar operator has at his disposal antenna positioning controls, a range-gate positioning control, an audio gain control and a switch for selecting manual or automatic receiver gain control. The principal adjustments during flight are antenna positioning in tilt (which rarely exceeds 30 degrees because beamwidth noise then becomes objectionable), antenna positioning in azimuth to allow for drift angle, and range-gate position. Although one might expect the radar operator to be satisfied to leave the range-gate position control set at a specified range for a given altitude, experience has shown that this is not the case. The variable range-gate control makes it possible for the operator to quickly scan the entire range, say from 1 to 10 miles ahead, for moving targets, and once a moving target is located to keep the target in the gate for a comparatively long period in order to learn as much as possible about it from the pitch and quality of its "musical" note.

In addition to the operating controls, the set is equipped with a built-in modulated echo-box testing device with which it is possible to make a routine overall performance check on the system, on the ground or in flight, with a modulated r-f signal

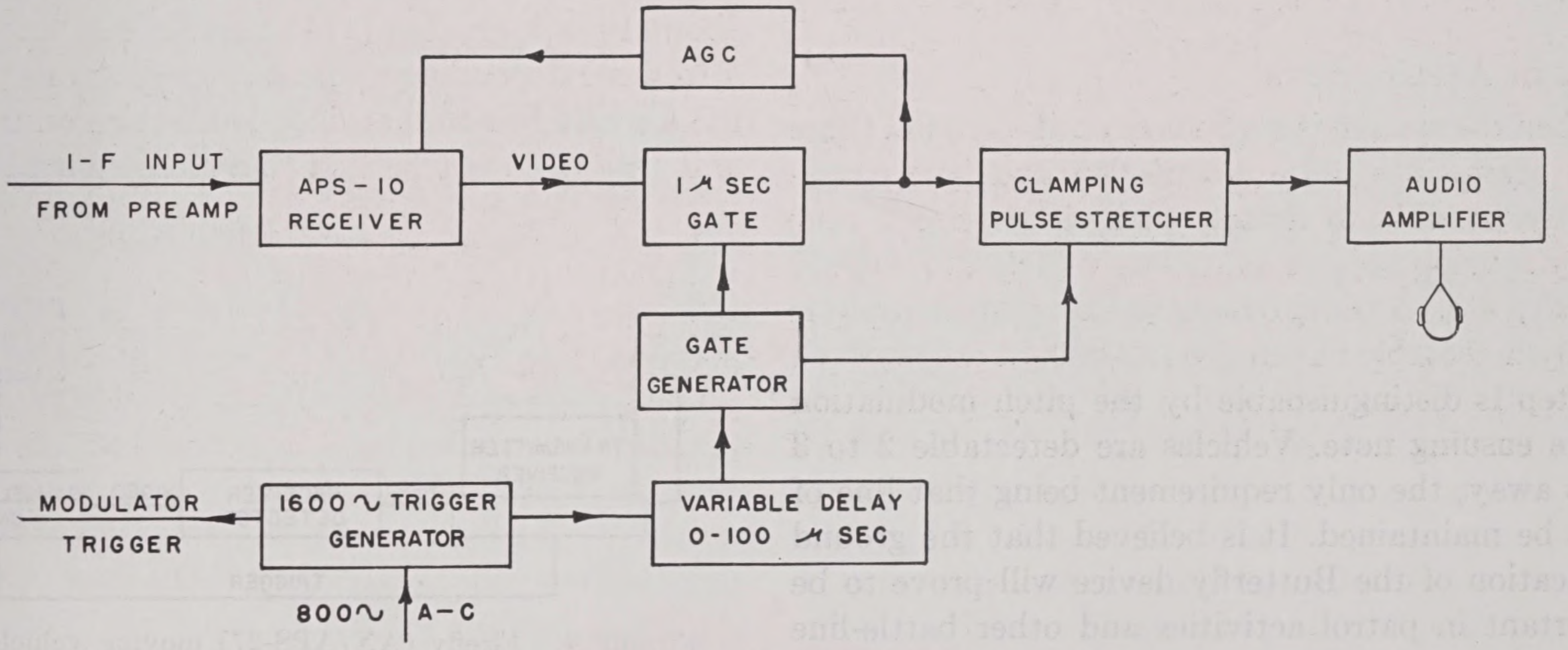

AGC
I-F INPUT FROM PREAMP
APS-10 RECEIVER
VIDEO
1 μ SEC GATE
CLAMPING PULSE STRETCHER
AUDIO AMPLIFIER
GATE GENERATOR
MODULATOR TRIGGER
1600∼ TRIGGER GENERATOR
VARIABLE DELAY 0-100 μ SEC
800∼ A-C

Figure 3. Butterfly synchronizer and detector.

simulating that from a moving vehicle. Such a test is extremely important. A detuned or otherwise inefficiently operated radar set is worse than no radar at all in this new type of radar reconnaissance mission, for although it is not customary to act on negative information still nonindication of vehicles might be interpreted by the military as meaning "no vehicles at all." This could lead to a false sense of security concerning the military situation in the region under surveillance.

24.1.3 Performance

Potentialities and Limitations

Some general performance figures for the Radiation Laboratory prototype are:

Maximum range: 10 miles (at least) on individual vehicles.
Minimum vehicle speed: 4 mph.
Minimum separation of vehicles: 250 ft for resolvable signals.
Maximum operating altitude: Over 18,000 ft.
Width of strip covered by beam: About 9 degrees (3,000 ft at 3 miles) for medium strength signals, much wider for strong ones.
Ship detection: Possible in sea clutter or along shore. Ordinary radar can be used in open sea.

The chief limitations of Butterfly are that it is not all-around-looking, and that close control of the aircraft is required. On the other hand, the system has high sensitivity and it gives an indication of the speed (hence, to some extent, the type) of the vehicle, which is something that no other system provides.

Ground Applications

When the system is stationary on the ground there is no beamwidth noise modulation and it is consequently possible to detect weak signals from very slowly moving objects as well as vehicles, low-flying aircraft, etc. A single man walking at 3 mph is readily detectable out to about 2,000 yd range. Each footstep is distinguishable by the pitch modulation of the ensuing note. Vehicles are detectable 2 to 3 miles away, the only requirement being that line of sight be maintained. It is believed that the ground application of the Butterfly device will prove to be important in patrol activities and other battle-line problems.

Characteristic Indications

The operator soon learns to tell something about the moving target from the characteristic quality of the note produced. The oscillograms in Figure 1 illustrate to some extent the influence of various factors upon quality.

24.2 FIREFLY (AN/APS-27) (PPI PRESENTATION)

24.2.1 General Description

Firefly[25] is a lightweight airborne radar system based on the noncoherent doppler phenomenon. It utilizes a mercury delay-line cancellation unit or a storage tube cancellation unit to eliminate ground clutter and to present only the moving vehicle echoes upon the *plan position indicator* [PPI] screen. Although the Firefly system arose to fulfill an urgent military need for the detection of moving vehicles at night or in foggy weather, other applications exist such as the detection of low-flying aircraft over land (anticollision radar), the detection of ship movements close to shore, drift angle determination, and in conjunction with the AN/APA-5 or AN/APQ-5 bombing aids, the bombing or strafing of moving vehicle targets. In this connection it should be noted that moving vehicles provide positive identification of themselves by virtue of their motion, in contrast to ordinary radar echoes which must be identified as targets by their shape, intensity, or configuration with respect to other targets. See Figure 1, Chapter 23 for a typical PPI photograph.

From the tactical standpoint, Firefly is far superior to Butterfly in many respects: it can provide 360-degree coverage and explore the area in a circle of about 10 miles radius (314 square miles) once every 3 to 6 sec depending upon the scanning rate; with it the aircraft becomes an independent reconnaissance unit that need not be tied to a close control center;

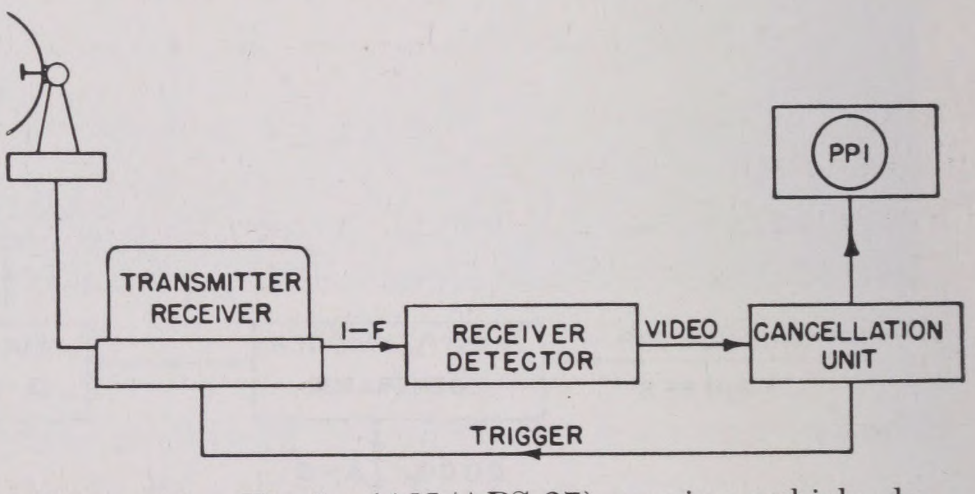
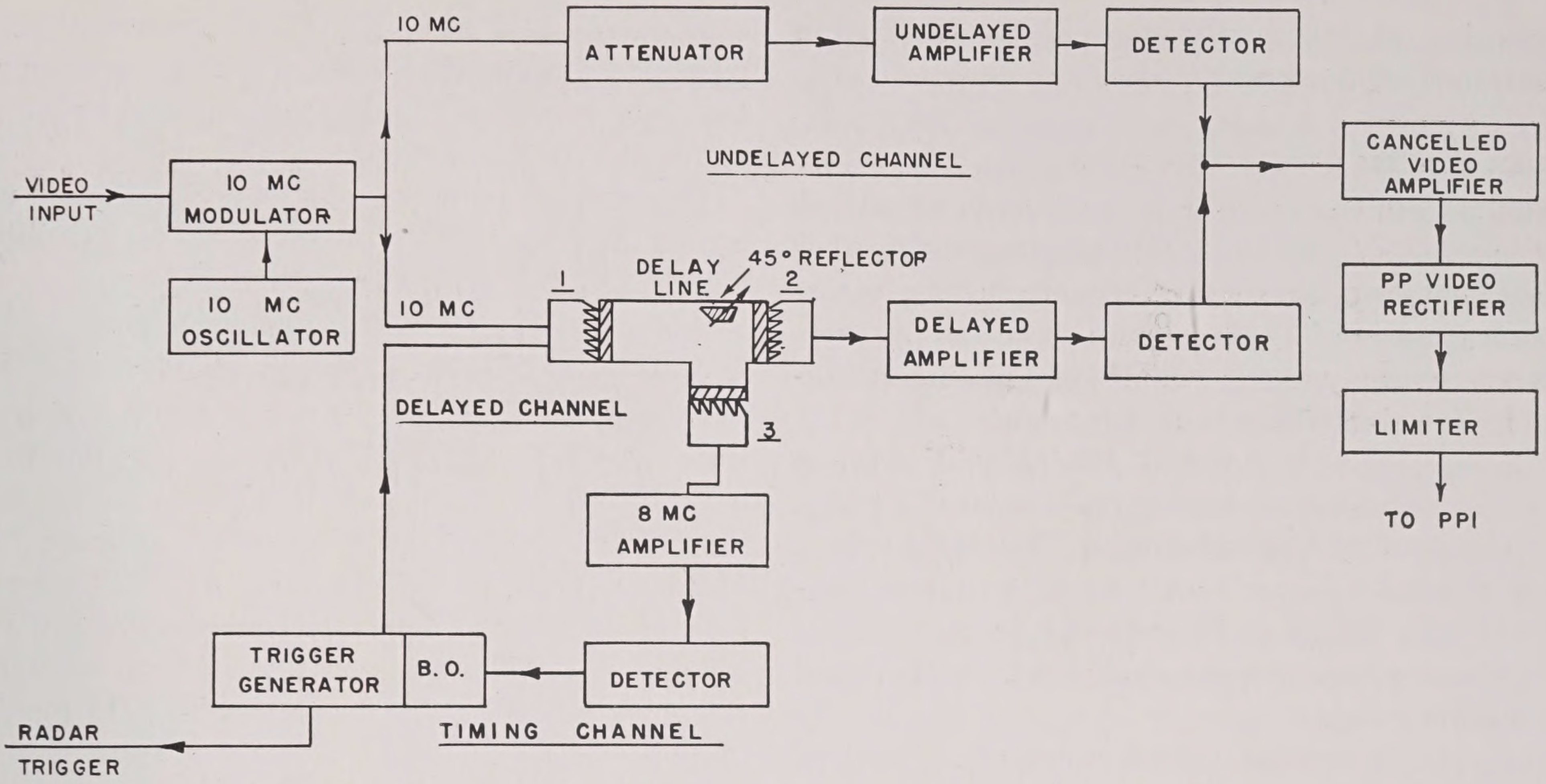
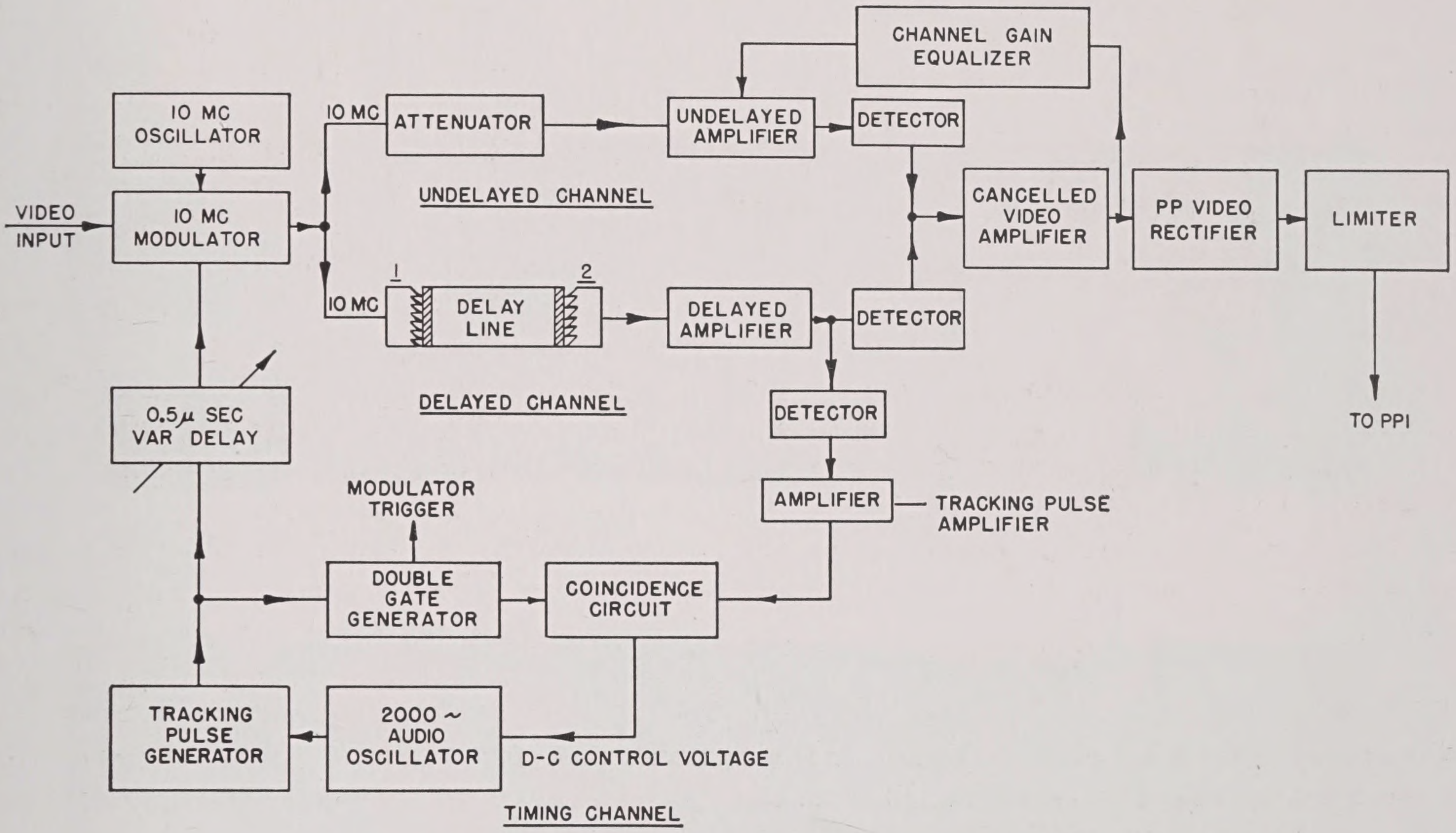


Figure 4. Firefly (AN/APS-27) moving vehicle detector. Simplified schematic block diagram.



VIDEO INPUT
10 MC MODULATOR
10 MC OSCILLATOR
10 MC
ATTENUATOR
UNDELAYED AMPLIFIER
DETECTOR
UNDELAYED CHANNEL
CANCELLED VIDEO AMPLIFIER
PP VIDEO RECTIFIER
LIMITER
TO PPI
10 MC
1
DELAY LINE
45° REFLECTOR
2
DELAYED AMPLIFIER
DETECTOR
DELAYED CHANNEL
3
8 MC AMPLIFIER
TRIGGER GENERATOR
B. O.
DETECTOR
TIMING CHANNEL
RADAR TRIGGER

Figure 5. Three-crystal cancellation unit. Simplified schematic block diagram.



CHANNEL GAIN EQUALIZER
10 MC OSCILLATOR
10 MC
ATTENUATOR
UNDELAYED AMPLIFIER
DETECTOR
VIDEO INPUT
10 MC MODULATOR
UNDELAYED CHANNEL
CANCELLED VIDEO AMPLIFIER
PP VIDEO RECTIFIER
LIMITER
1
2
10 MC
DELAY LINE
DELAYED AMPLIFIER
DETECTOR
0.5μ SEC VAR DELAY
DELAYED CHANNEL
DETECTOR
TO PPI
MODULATOR TRIGGER
AMPLIFIER
TRACKING PULSE AMPLIFIER
DOUBLE GATE GENERATOR
COINCIDENCE CIRCUIT
TRACKING PULSE GENERATOR
2000 ~ AUDIO OSCILLATOR
D-C CONTROL VOLTAGE
TIMING CHANNEL

Figure 6. Two-crystal cancellation unit (automatic temporal and amplitude cancellation).

it shows up entire lines of vehicles thereby providing characteristic outlines of the roadways and aiding in identifying priority targets; and, as mentioned above, it provides a means of immediate, independent, offensive attack upon the vehicles. Firefly is probably not so sensitive to slowly moving vehicles as Butterfly, and there is no means for telling something about the type of vehicle by examining the quality of the note as in Butterfly. However, the latter feature could easily be incorporated in Firefly if it were desirable.

24.2.2 Technical Description

The Firefly system is essentially a standard radar whose plan position indicator has a cancellation unit connected in series with the video lead to the PPI scope. A block diagram of the components of the system is shown in Figure 4. The following is a brief description of the components of the Radiation Laboratory experimental model.

RADAR SYSTEM CHARACTERISTICS

The transmitter-receiver is similar electrically to that in the AN/APS-10. A 2J42 magnetron furnishes approximately 6 kw peak power output at a recurrence frequency of 2,000 c, pulse duration 0.8 μsec. The power supply contains additional filters to eliminate modulation effects caused by hum.

The receiver is a modified AN/APS-10 strip, to which instantaneous automatic gain control is added to increase the dynamic range. This results in a linear type of receiver rather than the linear-logarithmic type which is theoretically more desirable but considerably more complicated, bulky, and power-consuming.

The antenna system utilizes standard X band r-f components and an AN/APS-15 cosecant-squared parabola. The standard AN/APS-15 sector-scan control box provides 360-degree scanning or limited sector scanning as desired.

The entire system, including the cancellation unit, presentation unit and power supply weighs approximately 200 lb installed in an aircraft.

CANCELLATION UNIT (MERCURY DELAY-LINE TYPE)

During the course of the development of the system, three different types of cancellation units were built and tested. Two of them contain mercury delay lines (fixed delay) and the third a storage tube. Mercury provides a fixed delay of 17.52 μsec per inch of mercury at 20 C with a temperature variation of +0.0052 μsec per inch per degree centigrade (mercury in steel). The delay time of both mercury units is 500 μsec.

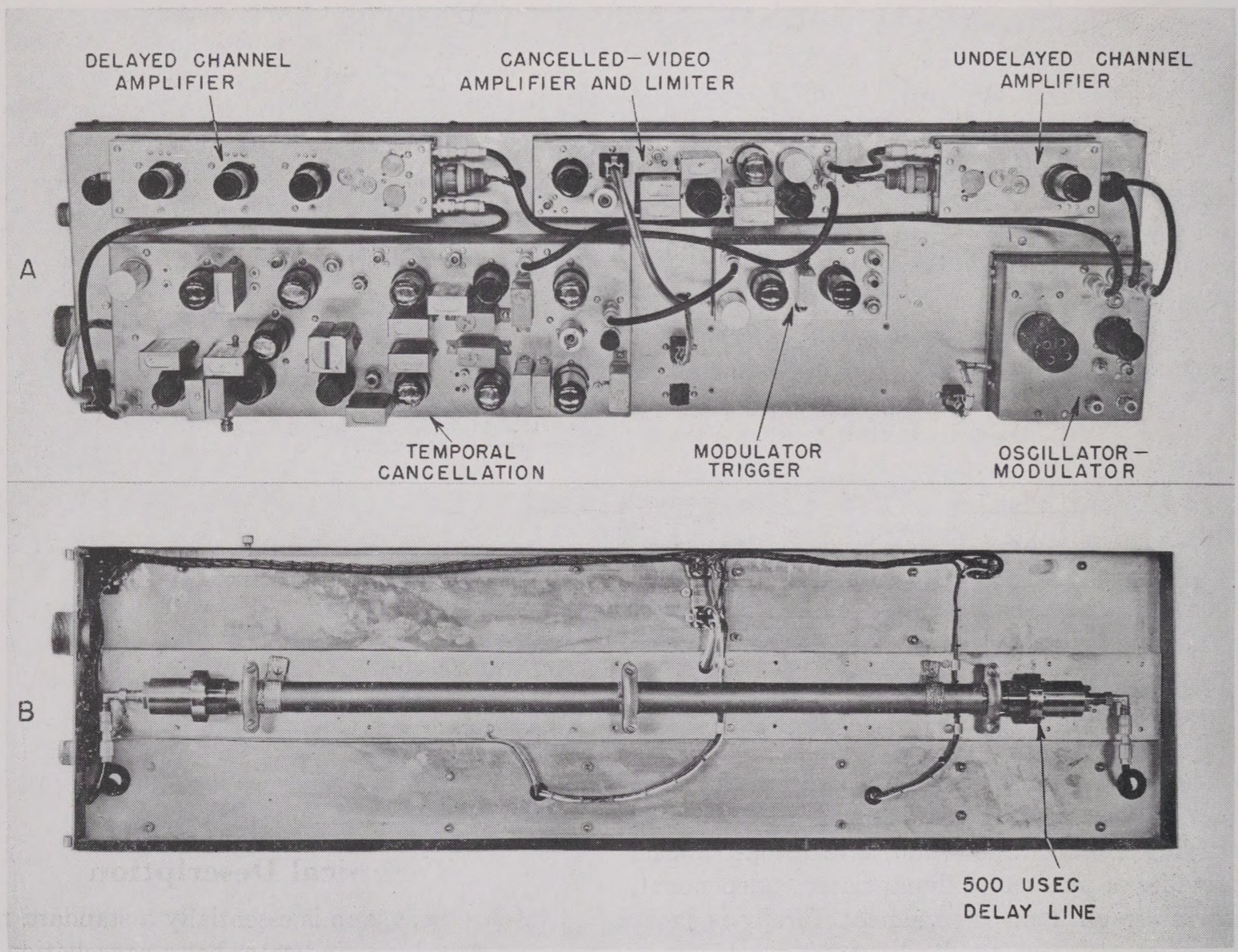

DELAYED CHANNEL AMPLIFIER
CANCELLED-VIDEO AMPLIFIER AND LIMITER
UNDELAYED CHANNEL AMPLIFIER
A
TEMPORAL CANCELLATION
MODULATOR TRIGGER
OSCILLATOR-MODULATOR
B
500 USEC DELAY LINE

FIGURE 7. Two-crystal Firefly cancellation unit, experimental model, showing the mercury delay line (underneath) and the components of the cancellation unit on top of the chassis. The automatic amplitude equalizing circuit is not shown.

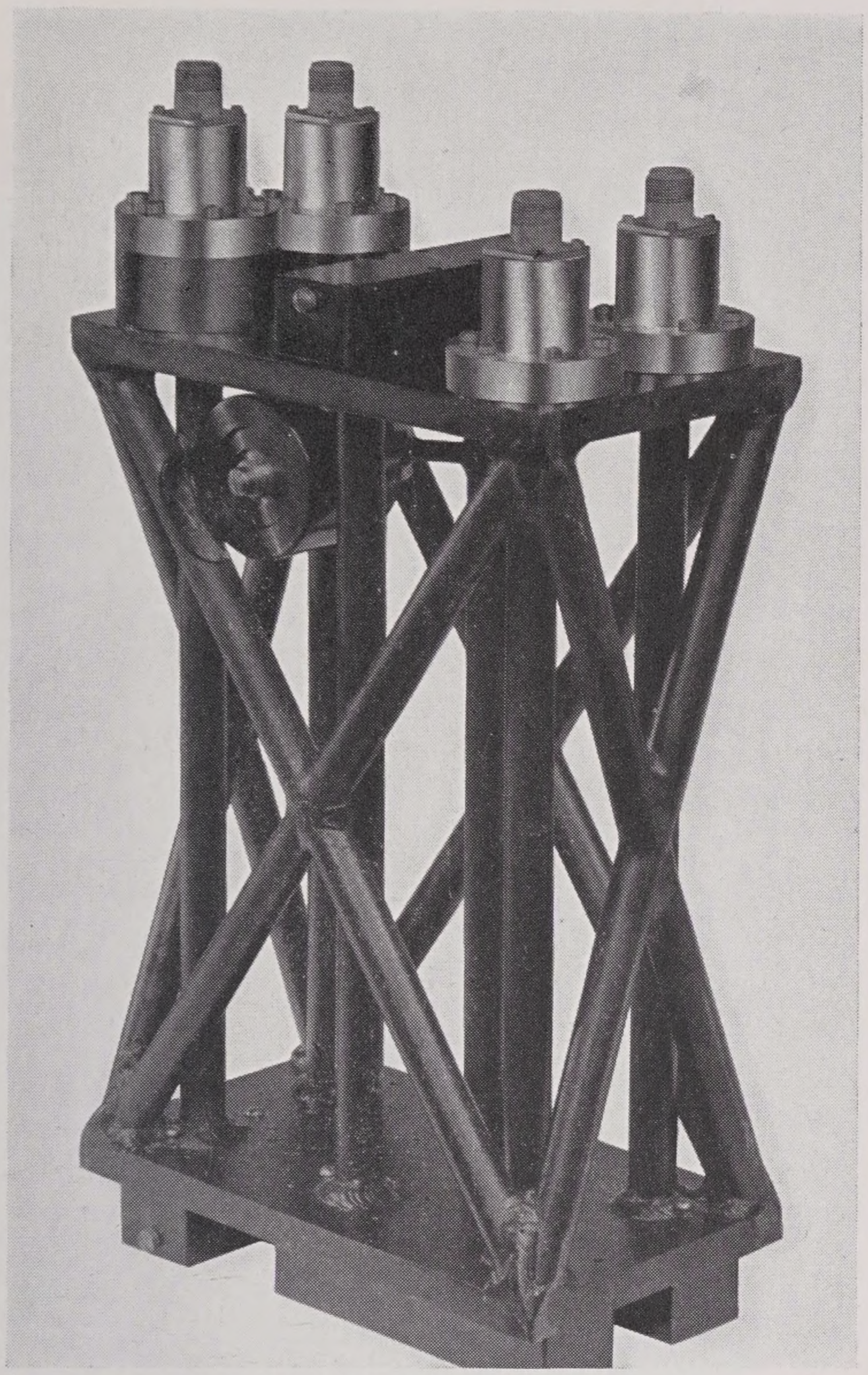


FIGURE 8. Double channel folded mercury delay line for AN/APS-20 (Cadillac). The right-hand pair of end-cells (containing the quartz crystals) are the input and output of the video delay channel which is folded so that the supersonic waves traverse a total path equal to four times the length of the unit. The timing channel (left-hand pair of cells) is folded once, and a gating circuit eliminates alternate triggers from the radar modulation.

The components of the 3-crystal cancellation unit are shown in Figure 5. In this unit, video signals from the radar pass into a 10-mc modulator and divide upon emerging, part of the power going into the 500-μsec line and the other part directly to the undelayed channel. The delayed video is picked up by crystal No. 2 in the mercury delay line, then amplified and passed into a detector. The delayed signal unites with the undelayed signal from the succeeding transmitted pulse at the output of the two detectors which are connected back-to-back so as to produce cancellation of video signals of equal amplitude. Amplitude-modulated signals are not cancelled and therefore can pass on to the cancelled-video amplifier, limiter, and thence to the PPI. In this way, only moving-target signals get through to the PPI.

Synchronization of the PRF so that the time interval between successive transmitted pulses corresponds exactly (to within 0.02 μsec) to the time delay in the line is accomplished in the timing channel loop which contains a trigger generator, crystals 1 and 3, the intervening mercury column, and the 8-mc amplifier and detector. The timing pulse originates in a blocking oscillator in the trigger generator, and passes into crystal No. 1 which it shock-excites to a frequency of about 8 mc. The shock wave travels down the line, strikes the 45-degree reflector block, passes into crystal No. 3, is amplified, detected, and triggers off the next pulse of the blocking oscillator in the trigger generator. The time delay between triggers is adjusted by moving the 45-degree block to produce best temporal cancellation of fixed echoes. The modulator trigger comes from the trigger generator.

Amplitude cancellation of signals from the delayed and undelayed channels is accomplished by adjusting an attenuator placed in the undelayed channel. The bandwidth of the undelayed and delayed channels is about 3 mc. The bandwidth of the mercury line is 4 to 5 mc.

The components of the 2-crystal, automatic temporal cancellation unit are shown in Figure 6. The operation of the 10-mc modulator, delayed channel, undelayed channel, back-to-back detectors, cancelled-video amplifier and limiter is identical with that of the corresponding components in the 3-crystal unit.

The timing-channel loop, however, is entirely different. Its function is to provide a control voltage for the 2,000-c timing audio oscillator, thereby controlling its frequency so that the recurrence interval will correspond exactly to the video delay introduced by the mercury line. The 2,000-c sine wave originating in the timing oscillator is sharpened by the trigger generator into a 1-μsec "tracking pulse." This pulse is fed into the double-gate generator and also through a short video delay (approximately 0.4 μsec) to the 10-mc modulator. The tracking pulse modulates the 10-mc carrier and travels down the line to the second crystal, then to detector No. 3, and through the tracking pulse amplifier to the coincidence circuit. This process requires approximately 500.5 μsec total (for a 500-μsec mercury delay line). Meanwhile, the next tracking pulse, 500 μsec later, generates the next

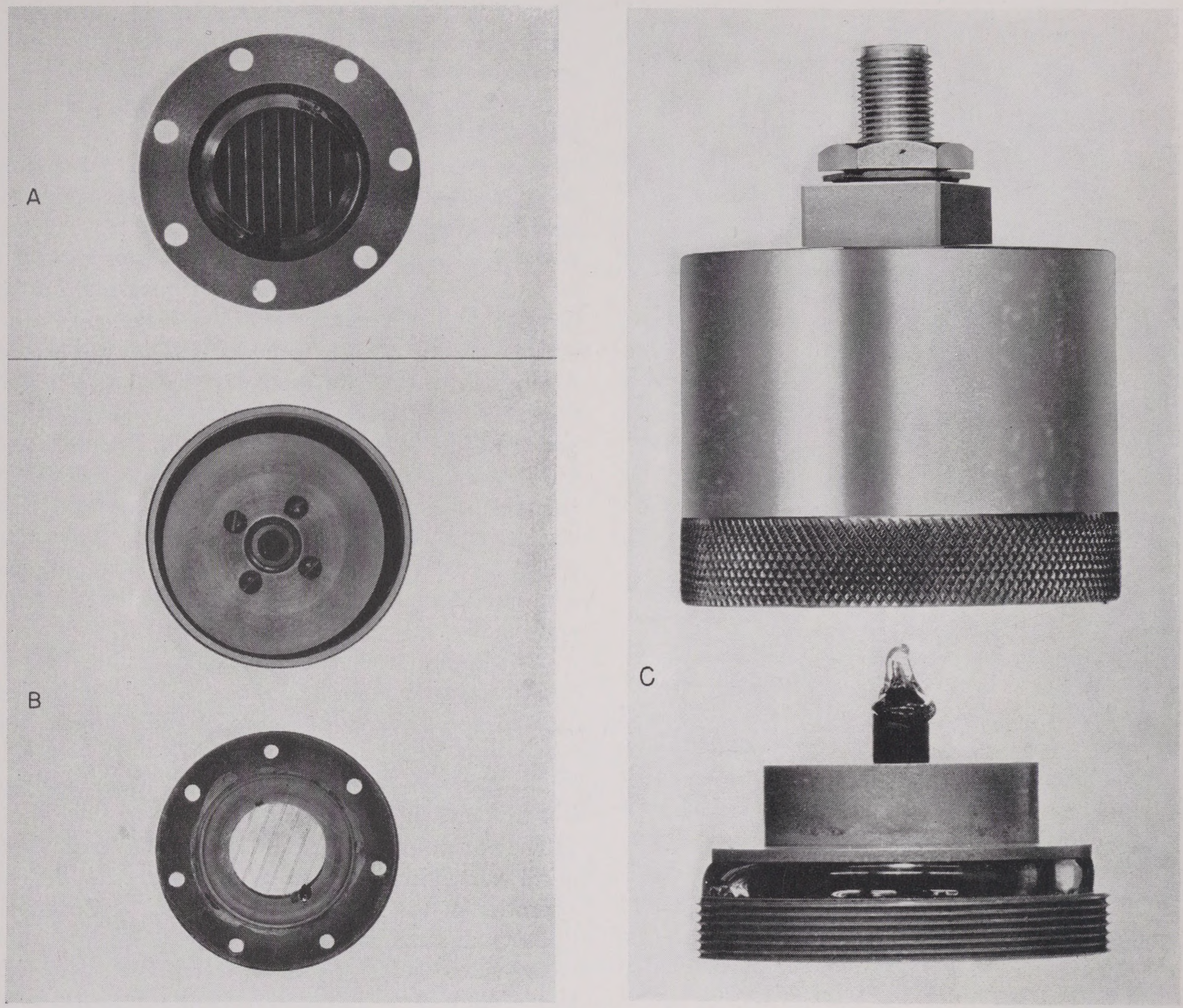


Figure 9. Absorbing end-cells with saw-tooth crystal support (A). The interstices between teeth are filled with mercury as shown in B (hermetically sealed type). Construction of unit is shown in C.

double gate, the center of which lies at 501.0 μsec (since the two gates are separated by 1 μsec and each one is 1 μsec wide). The center of the tracking pulse is also at 501.0 μsec (since the leading edge arrives at the coincidence circuit at 500.5 μsec and the pulse itself is 1.0 μsec wide). Consequently, the tracking pulse from the delay line lies equally in the two gates. As long as this condition remains unchanged, the d-c voltage output of the coincidence circuit remains unchanged, keeping the frequency of the timing oscillator constant. However, if the tracking pulse tends to lie more in one gate than the other, the d-c error voltage generator changes so as to alter the frequency of the audio oscillator thereby shortening or lengthening the recurrence time interval. In this way the recurrence interval is maintained identical with the video delay in the line. The variable delay section inserted between the signal generator and the modulator provides the means for initially compensating for circuit delay time. The modulator is triggered by a pulse from the double-gate system. Although the circuit is complicated, it successfully eliminates the problem of maintaining temporal cancellation.

The amplitude equalizing circuit suggested in Figure 6 serves to analyze the cancelled video of the tracking pulse. If amplitude cancellation is imperfect, there will be a residual signal, plus or minus, depending on the relative gain of the delayed and undelayed channel amplifiers. The function of the equalizer is to provide an automatic gain control voltage on the undelayed channel amplifier thereby equalizing the amplitudes at all times.

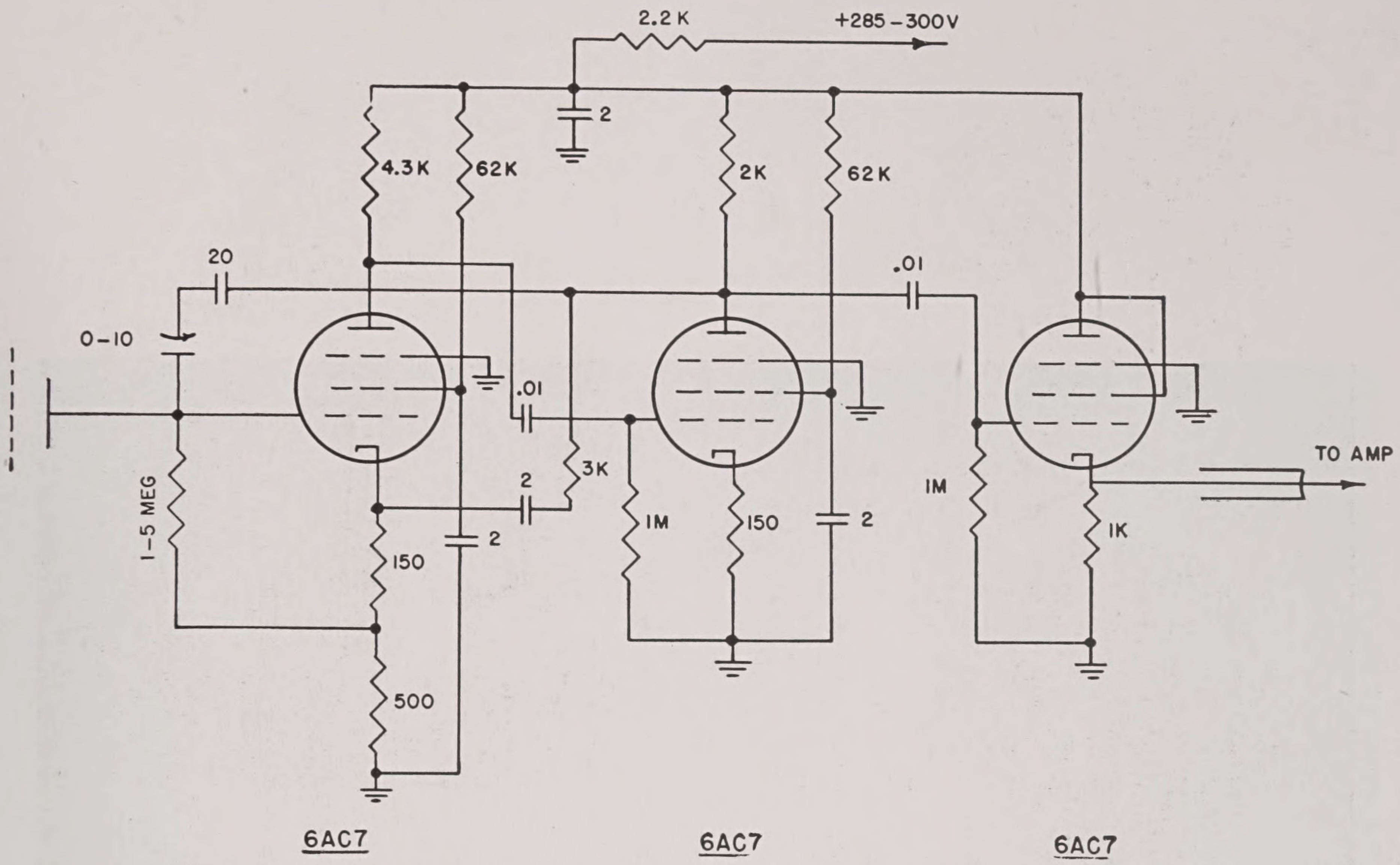


FIGURE 10. Low capacity input pickup amplifier for storage tube cancellation unit.

Two types of mercury delay lines are illustrated in the photographs in Figures 7 and 8. The attenuation of the 500-μsec line constructed of $\frac{3}{4}$-in. tubing is about 55 db. Reflections from the crystal faces at the ends of the line may be absorbed either in special mercury-backed saw-toothed supports for the crystals (see Figure 9) so that the power contained in the second traversal reflection of echoes is insignificant, or else in the line itself by introducing attenuation or varying other design parameters, for example, carrier frequency and line diameter. Cancellation ratios of uncancelled video signals to the same signals when cancelled range from 30 to 50 db in well-designed mercury delay cancellation units.

Solids, including quartz and aluminum, have also been utilized in delay lines. Further development of solid delay lines and end-cells is in process.

CANCELLATION UNIT (STORAGE TUBE TYPE)

As explained in Chapter 23, any fixed type of delay line has the disadvantage that it must establish the recurrence frequency of the system; on the other hand, the storage tube allows the recurrence frequency to be established by other means. One operational advantage of this is that the PRF can be varied, thereby eliminating blind speed regions. A second is that hum effects can be eliminated by synchronizing PRF with the a-c power frequency. A third is that the storage tube type may be somewhat lighter than the mercury delay line, thus making it more suitable for airborne use. The phenomenon of image storage on the cathode-ray tube face is described in Section 23.3.2, under "Storage Tube Type" and the major components of a storage tube cancellation unit are illustrated in Figure 5, Chapter 23. The heart of the system is the pickup amplifier which employs a feedback input circuit that effectively neutralizes the input capacity of the pickup plate, thereby providing reasonably good bandwidth in the high-impedance input stage, coupled with good signal-to-noise characteristics. The circuit diagram of the experimental model of the pickup amplifier is shown in Figure 10.

In the present stage of development the maximum length of sweep permissible on the 5-in. tube seems to be about 50 μsec. A longer sweep results in excessive reduction in resolution of adjacent signals. If a range greater than 5 miles is desired it would be necessary to employ a spiral trace or step trace on the A scope. Cancellation ratios of about 20 to 30 db are secured with the present type of tube and pickup amplifier. Best results are obtained with a low intensity, well-focused beam.

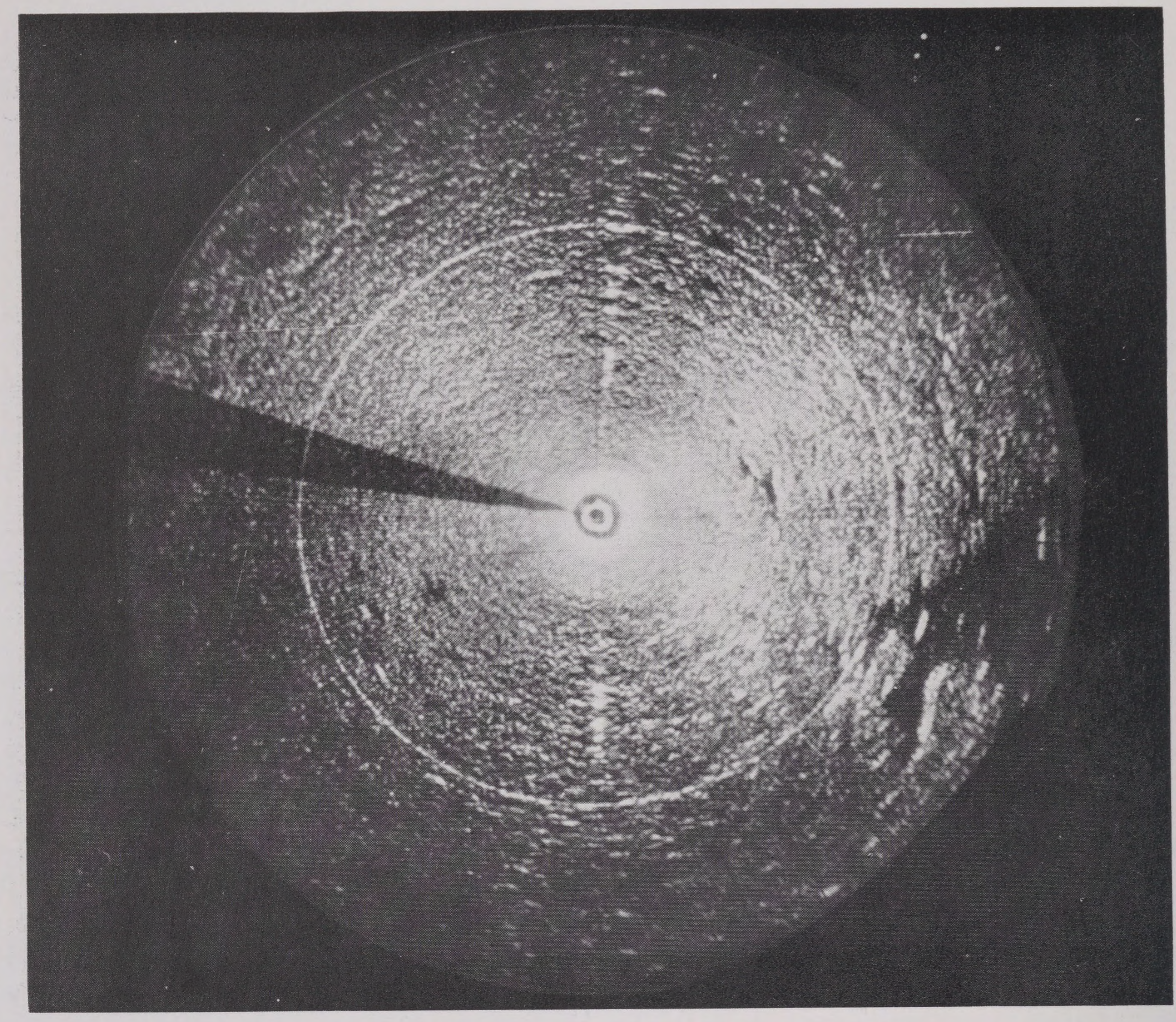


Figure 11A. Firefly. Vehicles on Newburyport Turnpike. Range circle of 5 miles. Details of the ground are "painted" in by mixing uncancelled with the cancelled video of the PPI. Heavy land painting.

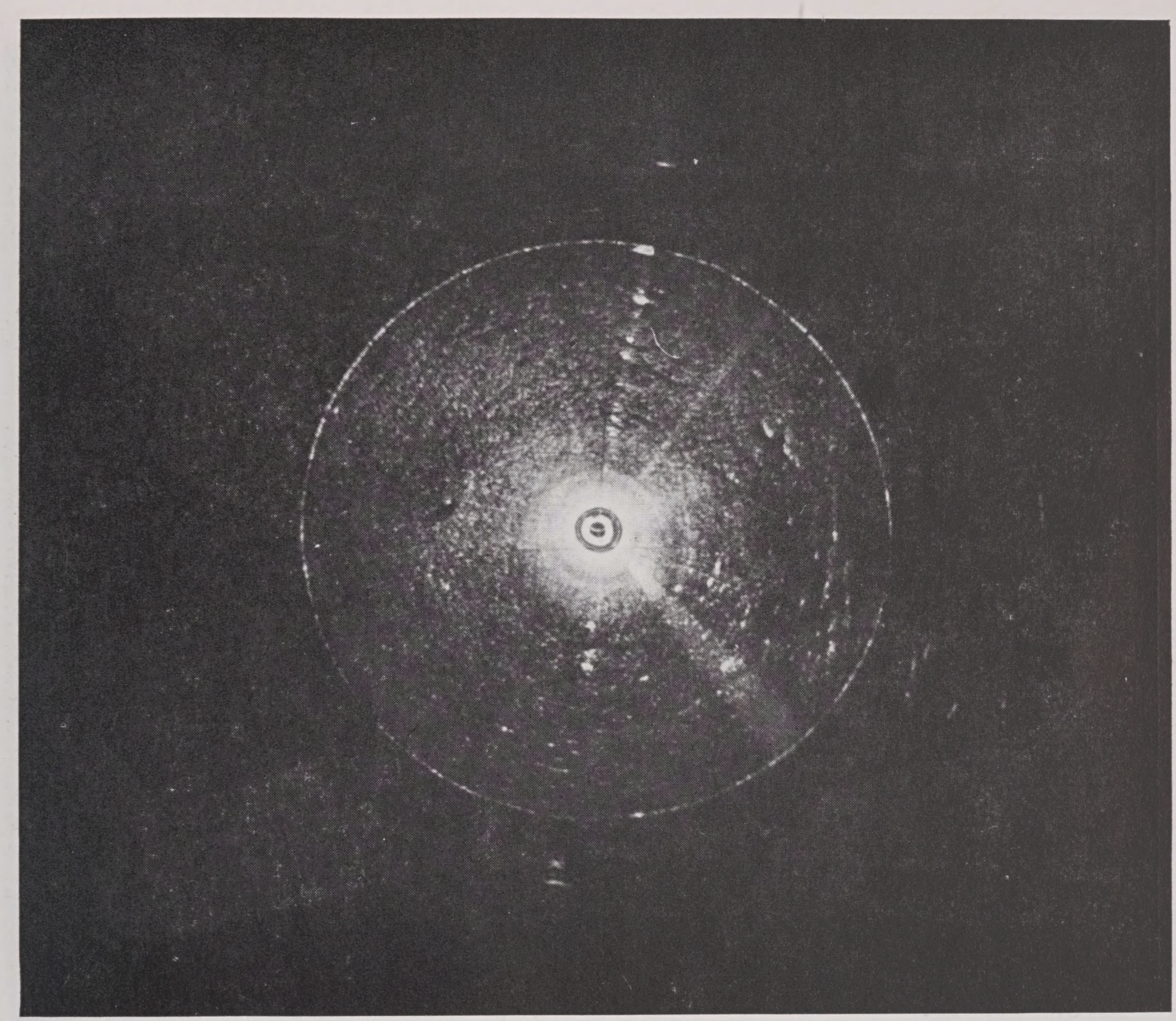


FIGURE 11B. Firefly. Vehicles on Newburyport Turnpike. Range circle of 5 miles. Details of the ground are "painted" in by mixing uncancelled with the cancelled video in the PPI. Medium land painting.

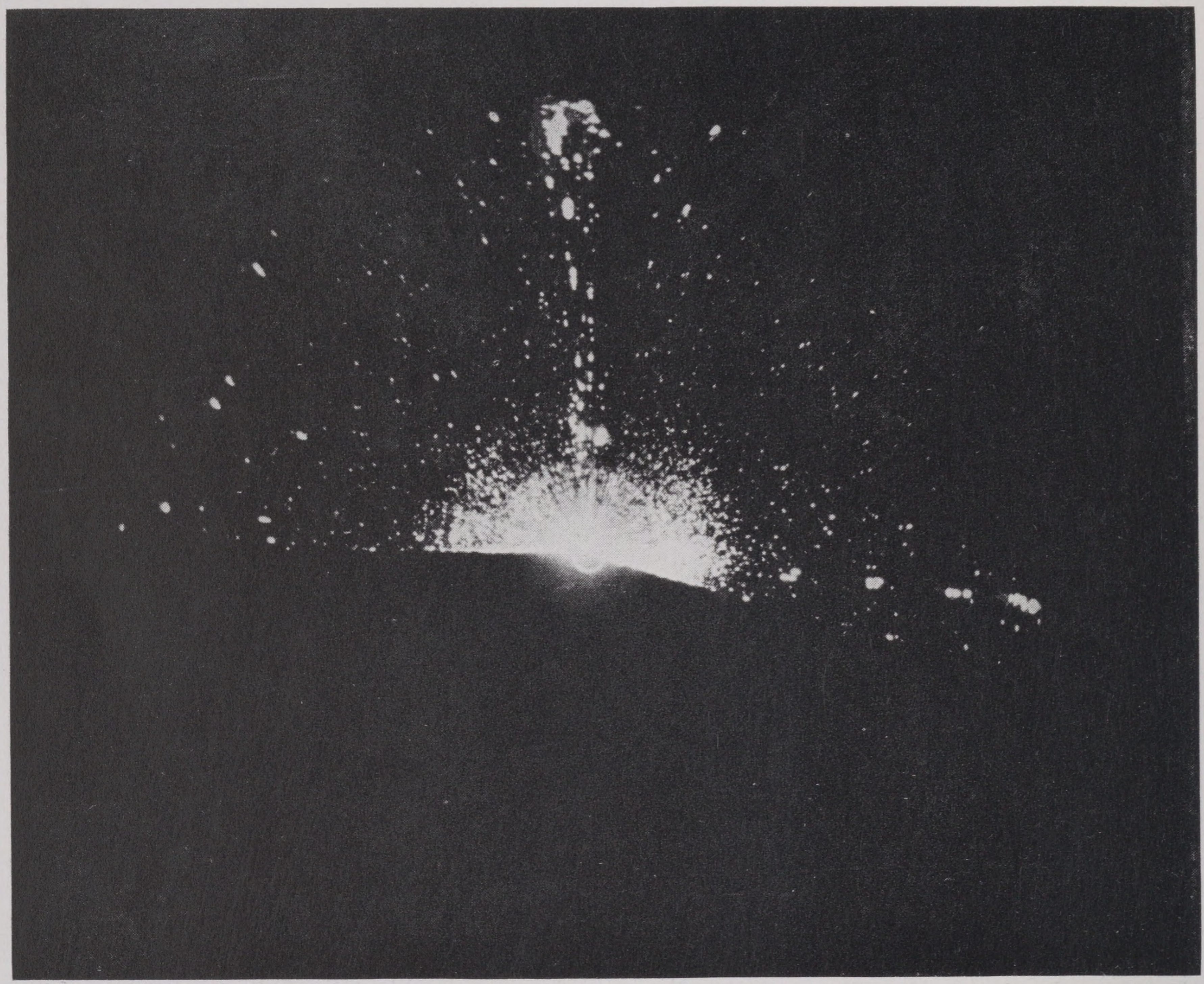


Figure 12A. Worcester Turnpike, approaching Boston. Sweep range about 4 miles — view showing multiplicity of moving targets seen on the approach to Boston.

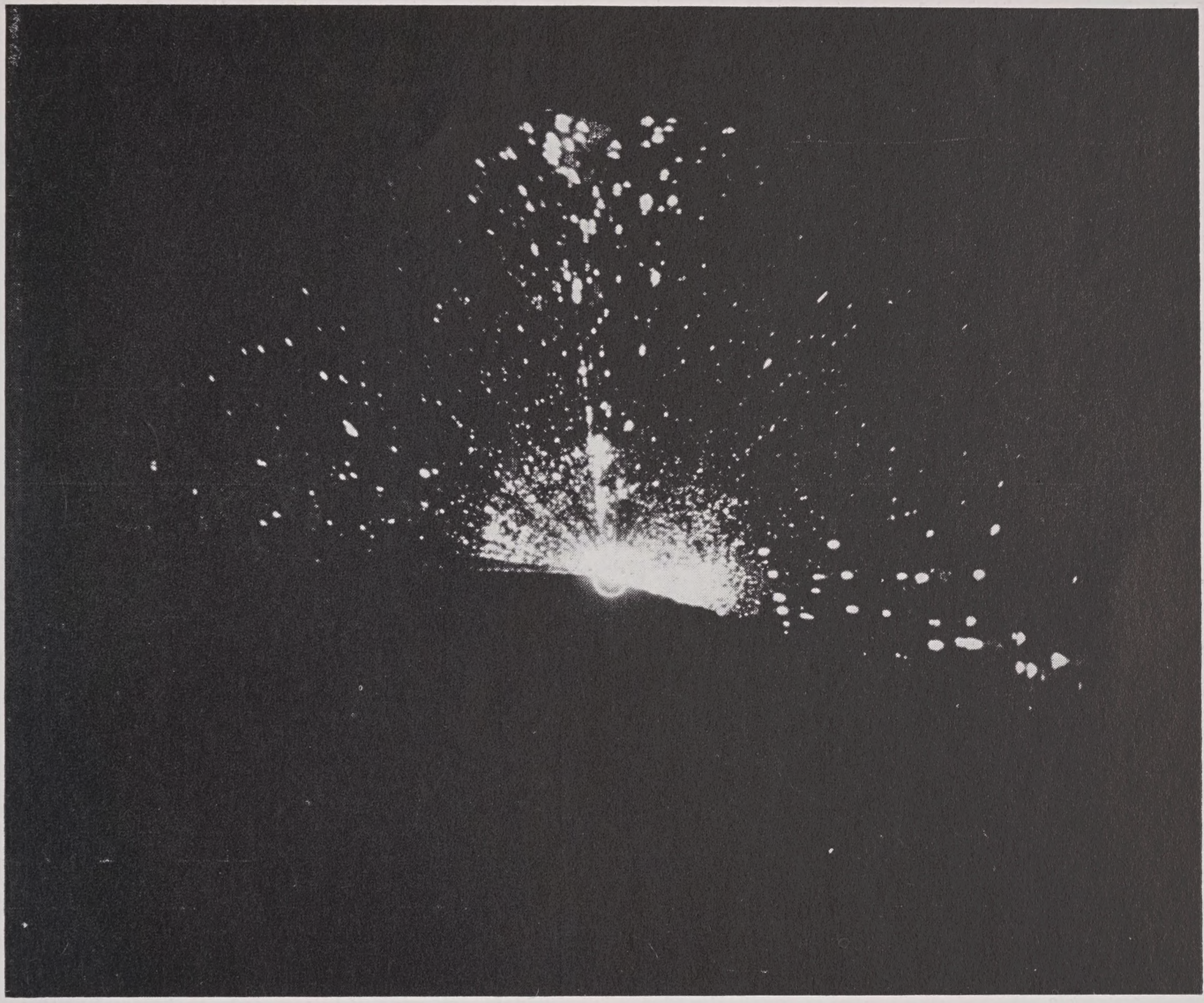


FIGURE 12B. Worcester Turnpike, approaching Boston. Sweep range about 4 miles — another view showing multiplicity of moving targets seen on the approach to Boston.

PRESENTATION

The photographs in Figures 1 and 3, Chapter 23, and Figures 11 and 12 of the present chapter show what may be expected from the Firefly system. High contrast presentation with low receiver gain is illustrated in Figure 1, Chapter 23.

In Figure 11 the effect of mixing cancelled and uncancelled video signals is illustrated. The uncancelled video "paints" a faint background of the terrain upon the tube face, thus aiding in navigation and in target identification. Even better results would have been obtained with a "duotone" or "three-tone" type of PPI in which the background painting is maintained at a uniform low level by a separate limiter on the uncancelled video.

OPERATION

Except for the additional function introduced by the cancellation unit, the operation of the Firefly system is only slightly more critical than that of a standard search radar. The cancellation unit requires two principal adjustments: temporal cancellation and amplitude cancellation. Temporal cancellation is achieved by minimizing the leading or trailing edge "spikes" on fixed echoes by fine adjustment of the PRF, and amplitude cancellation by minimizing amplitude noncancellation with the undelayed channel gain control. As in the case of Butterfly, it is recommended that an echo box be incorporated in the airborne equipment to allow the radar operator to test, at the flick of a switch, the overall performance of the set.

24.2.3 Performance

Except for reliability, the performances of the 3-crystal model (Model I) and the 2-crystal model (Model II) experimental cancellation units were not appreciably different. As may be seen from the photographs, vehicles are easily visible out to 10 to 12 miles ahead and 5 to 8 miles abeam for an aircraft flying between 2,500 to 5,000 ft altitude. Noncancellation wings are apparent in Figure 3, Chapter 23, where the receiver gain was high. Noncancellation also appears at large beam tilt angles (greater than 30 degrees). On one occasion, a small aircraft flying at 1,000 ft was seen out to the limit of the sweep (3 miles, at the time) when the Firefly aircraft was at 3,500 ft. The flight tests conducted at the Radiation Laboratory have not adequately explored the potentialities and limitations of the Firefly device.

24.3 AIRBORNE MOVING TARGET INDICATOR FOR CADILLAC (AN/APS-20) (HIGH–POWER, LONG–RANGE AIRCRAFT DETECTION)

24.3.1 General Description

The pulsed coherent doppler principle was applied to the high-powered "Cadillac" airborne early-warning radar to fulfill a definite military need.[23] The Cadillac system is so powerful that, when used over water, sea clutter obscures all aircraft out to ranges of 30 to 50 miles, depending upon the roughness of the sea, altitude of the radar and target aircraft, and other factors. The *airborne moving target indicator* [AMTI] system cancels the sea clutter and renders the Cadillac radar useful for aircraft detection at reasonably close ranges.

24.3.2 Technical Description

The Cadillac system [23, 26–28] operates at a pulse recurrence frequency of 1,000 c. It is an S band system. A hard-tube modulator with well-filtered power supplies supplants the original spark-gap modulator. A simplified block diagram of the components of the AMTI portion of the system is shown in Figure 13. The general principles involved are explained in Section 23.2.1 under "Coherent Pulsed-Transmission

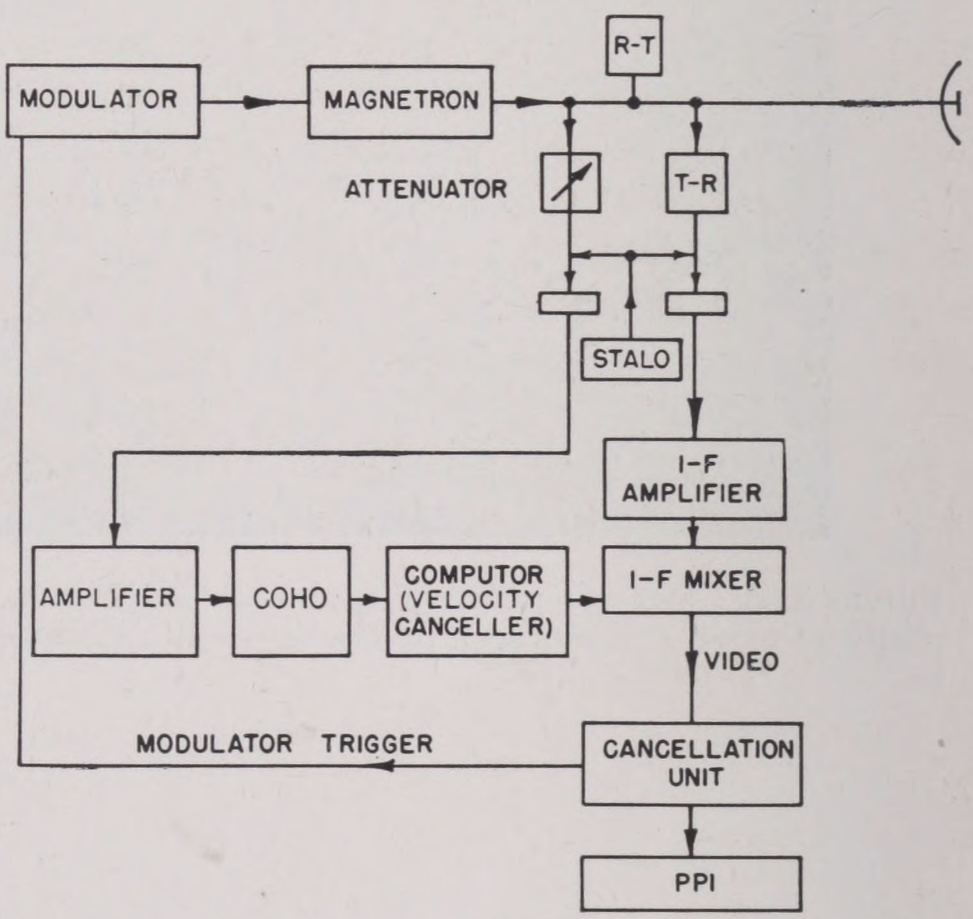


FIGURE 13. AMTI coherent pulsed doppler system. Simplified schematic block diagram.

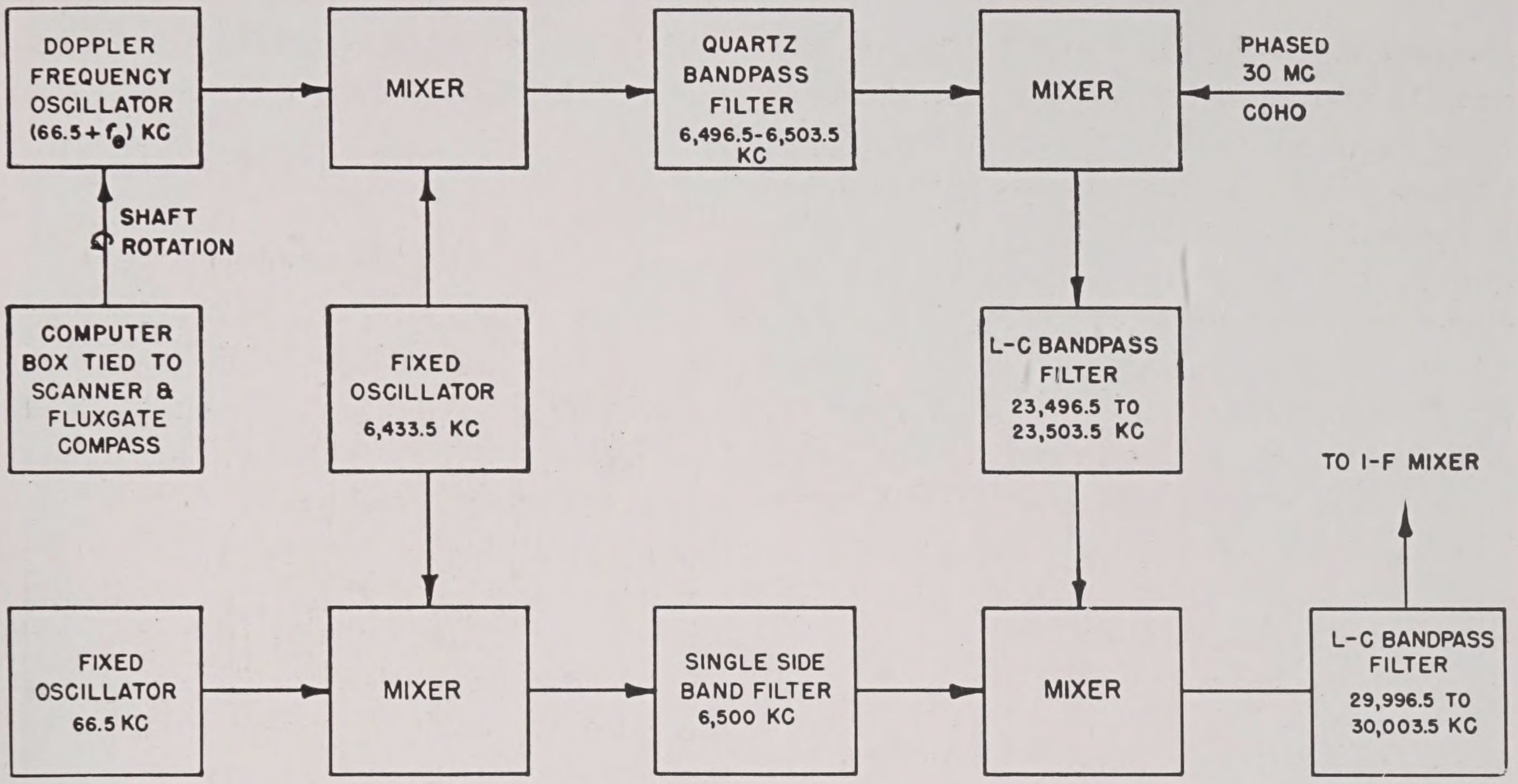

DOPPLER FREQUENCY OSCILLATOR (66.5+f$_\theta$) KC
MIXER
QUARTZ BANDPASS FILTER 6,496.5-6,503.5 KC
MIXER
PHASED 30 MC
COHO
SHAFT ROTATION
COMPUTER BOX TIED TO SCANNER & FLUXGATE COMPASS
FIXED OSCILLATOR 6,433.5 KC
L-C BANDPASS FILTER 23,496.5 TO 23,503.5 KC
TO I-F MIXER
FIXED OSCILLATOR 66.5 KC
MIXER
SINGLE SIDE BAND FILTER 6,500 KC
MIXER
L-C BANDPASS FILTER 29,996.5 TO 30,003.5 KC

FIGURE 14. Velocity cancellation computer for a 10-cm airborne coherent pulsed doppler system. The shifting frequency, f_θ can be varied from 0 (abeam) to ±3.5 kc (fore and aft) corresponding to a maximum ground speed of about 400 mph.

Doppler Method.” The transmitted r-f pulse from the magnetron beats with the *stable local oscillator* [STALO] and starts up the 30-mc *coherent oscillator* [COHO] in a phase which depends upon the combination of the STALO and r-f phases. The returning echo beats with the STALO and produces i-f whose phase depends upon the combination of the phases of STALO, r-f, and phase due to the range of the target. If the target remains at fixed range, then the phase of the i-f bears a *fixed* relationship with respect to the COHO. When the i-f and COHO are combined in the detector, the resulting video signal will be up or down, and its amplitude from pulse to pulse will be fixed. The phase caused by moving targets will change from pulse to pulse, and the video will show amplitude modulation. For the airborne system the fixed targets are also moving, and their motions can be cancelled out by introducing the proper phase shift in the starting phase of the COHO from pulse to pulse. This is accomplished in the computer box [23] where, by an ingenious system of high-frequency carriers and single-side-band amplifiers and detectors, the COHO, at 30 mc is mixed with an audio frequency f_θ of from 0 to 3,500 c to produce a new frequency equal to 30 mc $\pm f_\theta$. A block diagram of the phase shifter portion of the computer box is shown in Figure 14.

The present plan for the AMTI system calls for utilizing noncoherent pulsed doppler out to 10 miles range and the coherent system thereafter.

Modulator triggering is obtained from the cancellation unit, which utilizes a double-delay line, the shorter section of which is the time element in the triggering circuit. (See Figure 8.)

24.3.3 Performance

At the time of this writing, the complete AMTI system had not yet been flown, although all the components had been laboratory tested and all portions of the systems except the coherent oscillator had been flight tested. Figure 15 shows a representative PPI photograph taken on an early flight, using noncoherent pulsed doppler detection. Single aircraft have been seen out to about 70 miles over land with the system.

24.4 CONCLUSION

It is the writer’s opinion that the airborne moving target detection device can provide over land the same type of valuable aerial radar reconnaissance that is now provided over water by airborne ship-search sets. When employed against aircraft, the system could be used to provide the information for an airborne fighter control center. In long-range

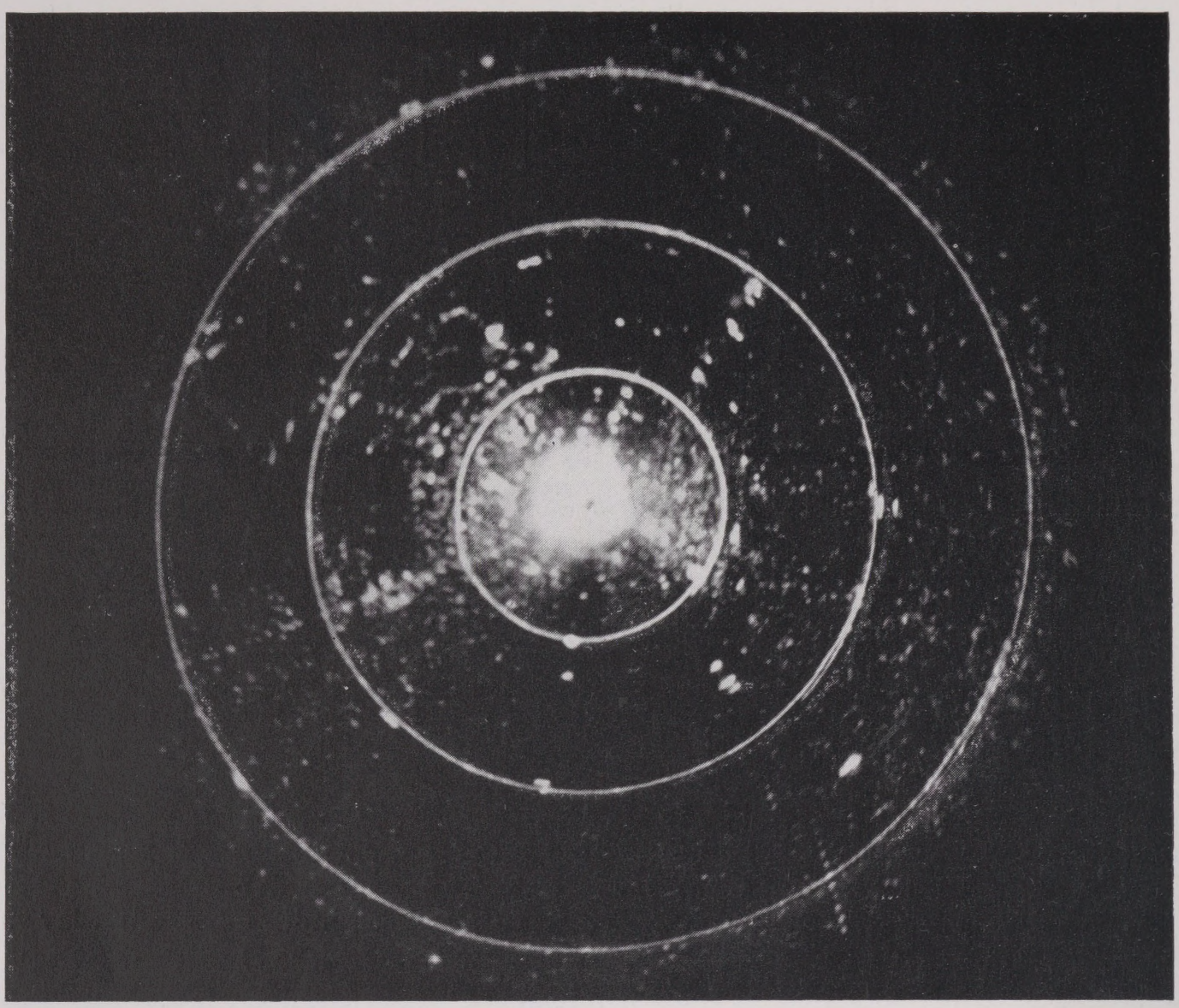


FIGURE 15. AMTI. Range markers are at 5-mile intervals.

bombing missions, bombers and their fighter escort could be controlled and coordinated as a single tactical unit by an accompanying airborne control center. Enemy fighters could be detected at great distances and adequate preparations made to meet or to evade them, whichever seemed to be the more desirable.

Like tanks, gun, and other implements of war the airborne moving vehicle detector probably has little peacetime application.

GLOSSARY

AEW. Airborne early warning (Cadillac). AN/APS-20 plus other components. A 10-cm radar system to be used primarily as cover for naval task forces. Radar information from an airplane is relayed to the aircraft carrier.

AFC. Automatic frequency control.

AGC. Automatic gain control.

AGL. Airborne gunlaying. Any completely automatic airborne gunlaying system.

AGS. Airborne gun sight. A manually operated gun-pointing system, in which the operator tracks from a scope indication.

AI. Aircraft interception. A general designation for systems for detecting one aircraft from another.

AIA. A 3-cm AI system for carrier-based fighter aircraft.

AIBR. Acceleration integrator bomb release (refers to toss-bombing).

Aided Tracking. A combination of displacement tracking and rate tracking, that is, the operator has direct single-knob control of both the position and velocity of some reference line, such as the sight line or the gun line.

Amplidyne. A d-c generator in which the response of the output voltage to changes in field excitation is very rapid; used extensively as part of a servo follow-up system.

AMTI. Airborne moving target indicator.

A–N Beam. Radio beacon to guide aircraft.

AN/. Indicates joint Army-Navy designation for a system.

AN/APA-. Designates an attachment to an airborne radar system.

AN/APA-5. LAB. An auxiliary radar bombsight to be used with a search radar such as AN/APS-1, -15, -30, especially for low-altitude bombing.

AN/APA-16. Automatic low-altitude bombing attachment for search radars.

AN/APA-40 (40-A). Micro-H Mk II. A delay unit for use with AN/APS-15 or AN/APQ-13.

AN/APA-46. Nosmo. An attachment for bombing radars designed to provide synchronous tracking, using the Norden sight.

AN/APA-47. Visar. A system similar to AN/APA-46 (Nosmo) in which the visual bombardier performs the radar bombing also.

AN/APG-. Designates airborne radar ("pulsed") gunlaying or gun-sighting systems; also includes rocket sighting systems.

AN/APG-1. A 10-cm AI and AGL system.

AN/APG-2. A 10-cm AI and AGL system.

AN/APG-3. A 3-cm gunlaying radar.

AN/APG-4. Sniffer. A 73-cm FM system for automatic bomb-release at altitudes up to 400 ft.

AN/APG-5. A 12-cm ARO system.

AN/APG-13 (13A). Falcon. A 12-cm range-only radar for 75-mm cannon and rocket fire against water targets and isolated land targets.

AN/APG-13B. Vulture or Overland Falcon. A 10-cm range-only conical-scan radar for cannon or rocket fire against land targets.

AN/APG-15 (15A, 15B). A 12-cm conical-scan AGS system.

AN/APG-16. A 3-cm gunlaying radar, similar to AN/APG-3.

AN/APG-19. A 3-cm gunlaying system.

AN/APG-21. Terry, Pterodactyl, or automatic Vulture. An automatic air-to-ground range-only radar, primarily for rocket fire.

AN/APN-1. A 68-cm FM radio altimeter, usable up to 4,000 ft.

AN/APN-19A. Airborne respondor beacon.

AN/APQ-5. LAB. A low-altitude bombing system.

AN/APQ-7. Eagle. A 3-cm bombing radar.

AN/APQ-13. H2X. A 3-cm high-altitude bombing and navigation radar for use over land, similar to AN/APS-15.

AN/APS-. Designates an airborne search or interception radar system; frequently adapted for bombing.

AN/APS-2. ASG. A 9-cm ASV and search radar.

AN/APS-3. A 3-cm medium- and low-altitude bombing radar.

AN/APS-4. ASH. A 3-cm ASV, AI and search radar for carrier-based aircraft.

AN/APS-6 (6A). A 3-cm search and interception radar, developed from AIA. Designed for carrier-based night fighters.

AN/APS-10. A 3-cm lightweight search and navigation system.

AN/APS-15, 15A. H2X. A 3-cm high-altitude bombing and navigation radar for use over land.

AN/APS-16. A 57-cm tail-warning radar.

AN/APS-19. A 3-cm search and interception radar.

AN/APS-20. AEW or Cadillac. See AEW.

AN/APX-15. Ella. Identification system (for B-29), depending upon propeller modulation.

AN/ASG-10. A nonradar toss-bombing system.

AN/CPN-2. Ground beacon for precision navigation.

AN/CPN-6. An X band ground respondor beacon.

AN/CPS-1. See MEW.

AN/CPS-6. V beam. S band early warning and GCI ground radar system.

AN/PPN-1,2. VHF respondor beacons for paratroops.

AN/TPN-1. VHF transportable respondor beacon.

AN/UPN-1,2,3,4. Ultra-portable respondor beacons.

Angle, drift. The angle, in the horizontal plane, between the longitudinal axis of an airplane and its path relative to the ground.

Angle of attack. The angle (measured in the vertical plane through the axis of the fuselage) between the line of flight of an airplane and some fixed reference line in the airplane, such as the line determined by the leveling lugs, the boresight datum line, or the zero-lift line. It varies with the speed, weight, and dive angle.

Angle off. The angle between the line of flight of an airplane (usually a bomber) and the line joining it to an aerial target; sometimes measured from the nose and sometimes from the tail.

Antenna. A conductor or system of conductors for radiating or receiving radio waves. A radar antenna includes the transmission-line feed or waveguide feed, the radiating elements proper, and the reflector.

Antenna, driven. An antenna which receives its power from the transmitter through the transmission line.

Antenna gain. A measure of the degree to which the radiation pattern is unidirectional; the ratio of the power per unit solid angle in the optimum direction to that from a source of equal power radiating isotropically.

Antenna, parasitic. An antenna which is not driven, but receives its current by induction from one or more other antennas.

Antenna pattern. The angular distribution of radiated power from the antenna assembly.

Antenna, yagi. Consists of a reflector behind and a series of "directors," shorter than half a wavelength, which are placed in a row in front of a driven antenna. A narrow beam of radiation is produced, with the maximum radiation in the direction of the line of centers of the antennas (end-fire parasitic array).

AR. Aircraft rocket.

Arma resolver. A device used to perform vector addition of a-c voltages.

ARO. An airborne range-only radar system; includes S band, X band, and FM systems.

ASB. A 60-cm Navy radar for surface search by carrier-based aircraft.

ASE. VHF airborne radar for surface search.

ASG. AN/APS-2.

ASH. AN/APS-4.

ASV. A radar system for detecting and homing on a surface vessel from the air.

ASVC. A 170-cm ASV system.

ATR. Anti transmitter-receiver. A gaseous discharge type of switch which when fired leaves the magnetron matched to the transmission line, but when it has recovered, presents a mismatch for echoes which return toward the magnetron, thus forcing them through TR to receiver.

Attenuation. Attenuation of a wave is the decrease in amplitude with distance along a transmission line in the direction of wave propagation, when the amplitude at any given place is constant in time.

Attenuator. A device for controlling the amplitude of a signal. There are two types of r-f attenuators, cutoff (operating on the principle of a waveguide below cutoff), and dissipative (series resistance, or shunt conductance).

Autosyn. A synchro device like the selsyn (q.v.).

AVC. Automatic volume control.

Bandwidth. The difference between specified frequencies (in cycles per second) of a frequency band; usually these are the half-power points in the frequency spectrum.

Base line. The horizontal or vertical line formed by the movement of the sweep on a cathode-ray tube with deflection-modulated presentation, for example, type A.

Beacon. An interrogated radar transmitter by means of which an aircraft can determine azimuth and range with respect to the location of the beacon.

Beamwidth. The angle between the half-power intensities of the radiation of an antenna.

Bias. A potential difference between the electrodes of a vacuum tube; usually applied to that between cathode and a grid.

Bias error. A constant error as opposed to a random error.

Black maria. A radar system for the identification of friendly aircraft, designed to be used with AEW.

Blocking oscillator. An oscillating vacuum-tube circuit containing a vacuum tube and a transformer, which produces pulses at a predetermined recurrence frequency. It may be free running or under control of a synchronizing voltage.

Bomb-release circle. For a given airspeed and altitude the locus of points at which a bombardier can release his bombs and hit the target providing he has the correct heading. This term is also applied to the electronic plot of such points on a radar scope.

B scope. Signal appears as bright spot, with azimuth angle as horizontal coordinate and range as vertical coordinate.

B′ scope. Similar to B scope, with elevation vertical and range horizontal.

BUPS. AN/UPN-1, -2.

BUPX. AN/UPN-3, -4.

Butterfly. Radar for detection of moving vehicles by an aircraft.

c. Cycles per second. The symbol ~ is also used for this term.

Cadillac. See AEW.

Cancellation unit. A delay unit in which signals returned from nonmoving targets are cancelled out.

Cathode-ray tube (CRT, oscilloscope, scope). A vacuum tube in which an electron beam is deflected by means of electric or magnetic fields. From the deflection, as observed on the face of the tube, the instantaneous values of the actuating voltages can be learned.

Central-station computer. An airborne gun-directing system which operates turrets by remote control.

CIT. California Institute of Technology.

Clamp. To hold the base of waveform or pulse to a given potential or current value.

Clutter. Radar signals from ground, sea, or other reflectors, appearing in an oscilloscope indication and interfering with observation of the desired target signals.

COHO. Coherent oscillator.

Coincidence Circuit. A circuit which transmits a pulse only when two or more input pulses coincide in time.

Conical scan. A system of scanning in which the axis of symmetry of the power beam describes a cone, usually of small angle. It is used when the angular position of a target must be known accurately.

Corner reflector. A metallic or metal-coated structure resembling the corner of a cube, particularly effective in reflecting a radar beam.

Cosecant-squared beam. A radar beam pattern designed to give uniform signal intensity for echoes received by airborne radars from distant and nearby objects. The beam intensity varies as the square of the cosecant of the elevation angle.

Countermeasures. Measures to combat enemy radar, such as jamming, window, antiradar paint, Schnorkel.

Crossover. The line about which the power beam from a conical-scan antenna revolves; also the relative power in the transmitted beam along that line in the antenna pattern.

Cross trail. See Figure 2, Chapter 6.

C scope. Presentation in which the signal appears as a bright spot with azimuth as horizontal coordinate and elevation as vertical coordinates.

CW. Continuous wave.

CXEH. A Navy beacon similar to AN/CPN-6, an X band ground respondor beacon.

db. Decibel, a unit used to express a power ratio. The number of decibels equals ten times the logarithm to the base 10 of the ratio of the two powers, e.g. "3 db down" means a 50 per cent loss of power.

Decay constant. The time required for a quantity to decay to 1/e of its original value. See time constant.

Delay. Refers to a delay in the passage of a current (or voltage) from one part of the circuit to another.

Delay line. An artificial transmission line which produces as output a duplicate of what was given to it a definite short time before.

Detail part. An element of an assembly, such as condenser, resistor, choke.

Director sight. In this the gunner controls the line of sight. As he tracks, the computer positions the guns; see disturbed-reticle sight.

Dipole (antenna). Two metallic elements, each approximately a quarter wavelength long, which radiate the r-f energy fed to them by the transmission line.

Dish. Antenna reflector.

Disturbed-reticle sight. A computing gunsight in which the gunner controls the gun line, and, as he tracks, the computer deflects the sight line from the gun line by the amount of the computed lead angle.

"Ditch." Abandon aircraft.

Doppler shift. A shift in the frequency of a wave caused by the relative motion of the source and receiver.

Drift angle. See angle, drift.

Driven antenna. See antenna, driven.

Drone. A pilotless aircraft.

Duplexer. An assembly (containing a TR tube) which directs the received energy to the receiver and excludes the very much greater transmitted energy. This allows the same antenna and transmission line to be used for both sending and receiving.

Duty cycle. Ratio of transmitter time on to repetition period, e.g., a 1-μsec pulse repeated every 500μ sec would have a duty cycle of 1/500. Duty ratio and duty are other terms for this. Duty factor is its reciprocal.

Eagle. AN/APQ-7.

Echo box. A high Q resonant cavity which receives r-f energy through a pick-up antenna during the transmitted pulse and reradiates this energy through the same antenna immediately after the pulse. The reradiated energy is picked up by the radar set. Since this energy from the echo box dies off exponentially, it will appear on an A scope indicator as a flat-topped pulse, resulting from the saturation of the receiver by the high energy return, followed by an exponential curve. The time from the end of the transmitted pulse to the time that the echo box signal is lost in noise is called the "ringing time" of the echo box. The echo box may be used to test the overall r-f performance of the radar set, and if the echo-box pick-up is in the antenna beam, the form of the antenna pattern can be shown graphically on the PPI.

Ella. AN/APX-15.

E plane. The plane of the electric vector of a beam of radiated power.

Eureka. Respondor beacon.

Expanded gain. The addition of a small portion of the indicator sweep voltage to the receiver gain voltage.

Exponential smoothing. A function $x = x(t)$ is said to be exponentially smoothed when it is replaced by $y = y(t)$ defined by the differential equation $k\frac{dy}{dt} + y = x$; see reference 58 in the Part IV bibliography.

Falcon. AN/APG-13A.

Firefly. A modification of Butterfly giving a PPI presentation.

FM. Frequency modulation.

Frame time. Time for a complete scan.

Frequency pulling. A change in the frequency of a magnetron or other oscillator caused by a change in the load impedance.

Future range. When the aircraft in Figure 1, Chapter 21 is at *A*, the distance *EC* is the future range.

Gain. A power ratio, usually referring to an amplifier.

Gain, Antenna. See antenna gain.

Gate. A square voltage pulse which switches a circuit on or off electronically.

GCI. Ground-controlled interception.

GEE. A British navigation and bombing technique.

GEE-H. A beacon-bombing system based on GEE equipment.

GPI. Ground position indicator.

Ground range. The distance from a point on the ground directly beneath an aircraft to a ground target or ground radar.

G scope. A type of indicator presenting a spot with wings, which grows as the target approaches; azimuth is the horizontal, elevation, the vertical coordinate.

GTAP. Ground track aiming point.

Gun-roll. A source of error in the computing of a lead by a gunsight arising from a neglect of one component of rotational motion.

Gyro sight. A sight in which the angular rate is measured by a gyroscope.

Harp Material. Antiradar coating; absorbs microwave frequencies.

H bombing. Bombing with the use of a navigational system in which the aircraft interrogates two ground beacons to determine its position.

Helipot. A helical potentiometer.

HF. High frequency; 3,000 to 30,000 kc.

H plane. The plane of the magnetic vector of a beam of energy.

H2S. S band bombing and search radars.

H2X. X band radars for bombing and search; includes AN/APS-15 and AN/APQ-13.

HVAR. High velocity aircraft rocket.

i-f. Intermediate frequency. In microwave radar, the i-f amplifiers are usually centered at 15, 30, or 60 mc.

IFF. Identification as friend or foe. Radar systems which usually "interrogate" and receive a coded response if the target is friendly.

Impact prediction. Computation of bomb-release point.

Indicator. A device for displaying a received radar signal; usually a cathode-ray tube, although a dial or drum recorder may occasionally be meant.

In-out switch. A switch for causing the range gates to unlock from a target signal and move to lesser or greater range.

Interrogator. A transmitting IFF radar set. Signals from it are received by a transpondor, and the latter replies automatically, this reply in turn being received by the respondor.

Intervalometer. A device for releasing a series of bombs at predetermined time intervals.

Jinking. Evasive motion of an aircraft in a series of straight line segments connected by curves.

J scope. A modification of type A in which the time sweep produces a circular range scale near the circumference of the CRT face. The signal appears as a radial deflection.

K band. Refers to wavelengths around 1 cm.

Killing drift. Changing the heading of an airplane to compensate for wind, so that its ground track will pass through a given target.

LAB. Low-altitude bombing; AN/APA-5 and AN/APQ-5 are examples.

Lead-computing sight. A gunsight which computes the angle between the bore axis of the guns and the line of sight which is necessary to obtain hits.

LHTR. Lighthouse transmitter-receiver.

Lighthouse tube. A small oscillator tube, so called from its appearance.

LO. Local oscillator; a tube which produces a signal with a frequency near that of the transmitter. The LO signal is mixed with the echo to give a "beat" at intermediate frequency which is then amplified and detected.

Lobe-switching. Directing an r-f beam rapidly back and forth between two or more positions.

Local turret. An airplane gun turret controlled by an operator located in it.

Longwave. Refers to wavelengths greater than 1 meter, as opposed to microwave radar.

Loran. A hyperbolic grid system of long-range radio navigation, in which the navigator observes the difference in arrival times of pulses from two known stations.

L scope. A double A scope presentation for a double-lobe system. Deflections to the two sides of the time sweep indicate signals from upper and lower (or right and left) lobes.

MAD. Magnetic airborne detector for submarines under water.

Magnetron. A transmitter tube which produces the main pulse of ultra high frequency energy. The flow of electrons is controlled by an applied magnetic field instead of a grid.

Major assembly. A self-contained combination of subassemblies and detail parts, such as indicator unit, transmitter-receiver unit, power unit.

mc. Megacycles per second. One megacycle is a million cycles.

MC-627. Automatic plotting table for close-support bombing.

MEW. Microwave early warning, a 10-cm ground radar for long-range detection or control of aircraft (AN/CPS-1); allows continuous plotting, in range and azimuth, of multiple targets.

Micro-H. H bombing with microwave radar systems.

Microsecond. μsec, 10^{-6} seconds.

Microwave radar. Radar using wavelengths less than one meter.

Mil. Abbreviation for milliradian, an angle of one-thousandth of a radian; one degree is 17.45 milliradians.

Mil, artillery. An angle equal to 1/6400 of a circle; one degree is 17.78 artillery mils.

Milliradian. See mil.

MIT. Massachusetts Institute of Technology.

Modulation. Varying the amplitude of the high-frequency signal according to a definite pattern.

Modulator. Also called a pulser. The part of the radar set which sends the high-voltage pulse to the transmitter. This pulse, in turn, starts the oscillation of the transmitter, which emits microwave radiation.

M scope. Modification of type A for range finding. The horizontal sweep is displaced vertically as in a step; the position of this step can be adjusted by some controlling device so that it coincides with the signal, at which point the device registers range.

MTI. Moving target indicator.

Multivibrator. A form of relaxation oscillator, essentially a two-stage amplifier with feedback. It will oscillate of its own accord or through an external synchronizing voltage.

Mush. A vague descriptive term associated with the phenomenon of angle of attack of an airplane. An airborne fixed gun is said to mush when its bore axis is elevated above the line of flight.

MV. Multivibrator.

MX-344. A bombing computer.

NDRC. National Defense Research Committee.

Noise. A random voltage appearing at the output terminals of a receiver with no impressed signal, if the amplifier has sufficient gain. On the A scope, noise appears as random spikes ("grass") on the sweep line. It is caused by random motion of electrons in the grid circuit of the first amplifier tube, fluctuations in emission, shot noise at the plate, etc.

Noise figure. The figure of merit for sensitivity of a receiver. Defined as the ratio of the input power to kTB (where k is Boltzmann's constant, T the temperature in degrees Kelvin, and B the bandwidth in c) when the output signal power equals the output noise power. Noise figure is normally expressed in decibels.

Nosmeagle. Nosmo for Eagle.

Nosmo. AN/APA-46.

Oboe. A British bombing technique.

Offset bombing. Bombing in which the bombardier (visual or radar) sights on an aiming-point different from the target.

OSRD. Office of Scientific Research and Development.

Own-speed sight. Same as vector sight.

Palmer scan. A type of antenna scan for searching.

Parasitic antenna. See antenna, parasitic.

Pass-band. Range of frequencies passed by a filter.

PDI. Pilot's direction indicator.

Phantastron. A precision delay circuit.

Plane of action. The plane containing the line of motion of an aircraft and the target.

Plumbing. Wave guide and coaxial cable or transmission line, with fittings.

Polyrod. Polystyrene plastic rod.

Position firing. A rule-of-thumb procedure for use by an aerial gunner whose gun is equipped with a ring and post sight. The lead taken depends only upon the relative bearing of the target.

PPI. Plan position indicator. Scope indication with circular sweep, showing ground objects in approximately correct relationship as on a map.

Pressurize. The filling of the r-f line with air at a pressure greater than atmospheric. Its purpose is twofold: (1) to prevent breakdown of the components at high altitudes and (2) to protect against transmission losses caused by materials in the atmosphere, such as dirt and water.

PRF. Pulse recurrence frequency.

Probable error. A magnitude associated with the measurement of a quantity such that half of the errors are less and half are greater than the given magnitude.

Proximity fuse. A fuse for shells, bombs, or rockets which sends out radio waves and explodes at a predetermined distance from a target (VT fuse).

Pulse. Refers to the emission of power for a short time, followed by a period of no emission; one of the fundamental characteristics of most radar.

Pulse shape. The graph of radiated energy as a function of time.

Pulsed doppler shift or principle. See Part V.

Pursuit course. A course in which a pursuer is continuously moving in the direction of the pursued; see Section 21.1.1 for more complex modifications of this concept, such as lead pursuit, aerodynamic pursuit, and aerodynamic lead pursuit course.

Q (of a resonant system). The Q of a specific resonance mode of a system is 2π times the ratio of the energy stored to the energy lost per cycle, when the system is excited in this mode. A high Q circuit is lightly damped, has a small decrement, a sharp resonance peak, and a high selectivity. Q is a figure of merit.

Radar. Abbreviation of "radio detection and ranging"; usually refers to systems using ultra-high frequency waves, with the pulse technique.

Radiation laboratory. In this book this designation is reserved for the MIT Radiation Laboratory which carried on radar research and development from 1940 to 1945, under the direction of Division 14, NDRC.

Radome. A general name for radar turrets which enclose antenna assemblies.

Range, future. See future range.

Range mark. One of a series of spots or lines on a scope to indicate the range of target signals.

Range wind. The component of the wind in the direction of the target.

Rate end. A component of the Norden sight.

Rate sight. A gunsight in which the lead is computed from the rate of tracking of the target.

RC network. A circuit containing resistances and capacitances.

RC-294. Plotting board for SCR-584.

Receiver sensitivity. Related to the ability of a receiver to detect weak signals. It is measured by the noise figure (q.v.) in the case of microwave radar.

Reflector, corner. See corner reflector.

Responsor. See interrogator.

r-f. Radio frequency. A general term for the frequency to be radiated, not confined to any specific limit.

r-f head. A major assembly unit of a radar system which includes the magnetron, duplexer, part or all of the receiver, and occasionally other parts.

Ringing circuit. A circuit in which the oscillations die out slowly, as when a bell is rung.

Ringing time. See echo box.

RL. Radiation Laboratory.

Saw-tooth sweep. A sweep in which the motion of the electron beam is controlled by a saw-tooth voltage wave, that is, the voltage rises slowly and linearly and then declines rapidly.

S band. Refers to wavelengths of the order of 10 cm.

Scanner. A device which directs the r-f beam successively over all points in a given space.

SCI. Ship-controlled interception. Similar to GCI.

Scope. Oscilloscope, cathode-ray tube. For the various types of scope presentations, see under the appropriate letters.

SCR. Signal Corps radio set.

SCR-520. A 10-cm airborne search and interception radar.

SCR-540. A 155-cm airborne radar for detection of other aircraft.

SCR-584. Mobile medium-range search and track radar, designed for antiaircraft fire control, and also applied to ground control of aircraft.

SCR-695. A 160- to 191-cm transpondor.

SCR-717. An airborne radar system for detection of surface vessels.

SCR-718. A 68-cm pulsed altimeter for use up to 40,000 ft.

SCR-720. A 10-cm airborne search and interception radar, especially for night fighters.

SCR-729. An IFF interrogator-responsor.

Second detector. The detector which converts i-f (30 or 60 mc) into video.

Sector scan. Motion of the scanner reflector back and forth through a limited angle, instead of through 360 degrees.

Selsyn. A self-synchronous motor or generator (autosyn, synchro; the latter name has been chosen by the Services). A means of making a shaft rotate by the same amount as another shaft at some remote position.

Servo-amplifier. The amplifier of power impulses in a servo system.

Servo loop. That collection of elements in a servomechanism which measures the error in the quantity to be controlled and applies a correction tending to reduce that error to zero.

Servo system. A mechanical, frequently an electromechanical, system for transmitting accurate mechanical position from one point to another by electrical or other means. The position is corrected by feeding back an error signal.

Shoran. Short range navigational system made up of two ground radars (AN/CPN-2) and one airborne set (AN/APN-3).

Side lobe. A portion of the beam from a radar antenna other than the main lobe; usually much smaller.

Sinepot. Sine potentiometer.

Skid (of an airplane). Motion of an airplane in a direction different from that in which it is heading.

Skywave. A radio wave reflected from the ionosphere; this occurs at frequencies less than 20 mc.

Slant range. Range from an aircraft to a ground target or radar; distinguished from ground range.

Sniffer. AN/APG-4.

Spinner. Rotating antenna assembly; a scanner.

SS loran. Sky-wave synchronized Loran.

Stability (of a sighting system). Stability exists when, if the gun is given a small quick jerk in some direction, the reticle is jerked in the same direction.

Stabilize (as a scope or line of sight). To maintain a system in a desired orientation, in spite of motion of aircraft or ship.

Stadiametric ranging. Determination of range to an airplane target by bracketing the image between optical markers in the sight, which then computes the range by the principle of similar triangles.

Stalo. Stable local oscillator.

Subassembly. A part of a unit assembly, replaceable as a whole, consisting of a combination of detail parts (q.v.), such as i-f amplifier section, voltage regulator.

Sweep. The beam of electrons passing from the electron gun to the face of the CRT makes a point of light on the face of the tube. By proper voltage or magnetic control this point of light can be made to move in any direction. By making this motion rapid and continuous, the point of light becomes a line of light, and is called a sweep.

Sweep circuit or generator. A circuit which produces at regular intervals an approximately linear or circular, or other form of movement (sweep) of the beam of the cathode-ray tube.

Synchro. Same as selsyn, autosyn. This designation is preferred by the Services.

Synchronization (of a bombsight). Establishment of the proper rate of motion of the bombing computer index so that the index tracks the target.

Synchronization (of a gunlaying system). Establishment of the tracking of a target in range and angle by the gunlaying system.

Terry. AN/APG-21.

Test equipment. An assortment of instruments provided with a radar set to enable the maintenance man to determine accurately whether the set is performing properly in its various functions and to aid in locating improperly operating components and in restoring them to proper condition.

Thermistor bridge. A bridge with sensitive resistors whose resistance varies significantly with temperature.

Time base. The sweep on an indicator tube begins at zero time, the instant that energy is transmitted and ends at a later predetermined time. It may be called a time base. Since time and distance are proportional in the radiation of the energy from its source, the distance of any signal on the sweep from the beginning of the sweep may be translated into units of geographical distance. In some circuits, the beginning of the sweep is delayed for a fixed or variable time after the firing of the transmitter. It is then known as a delayed sweep.

Time constant. The time required for a variable which obeys an exponential law to change by a fraction 1/e of the total change.

TR. Transmit-receive tube; a TR box or, preferably, switch, is the assembly containing the TR. See duplexer.

Trail. The vector giving the displacement of the actual point of impact of a projectile or bomb from the point where it would have hit if it had moved in a vacuum.

Trajectory drop. The angle (in mils) between the line along which a projectile was fired and the line from the gun to the position of the projectile.

Transpondor. A radar system which receives and replies to an IFF interrogator (q.v.). Also a similar system used as a radar beacon for navigational purposes.

TRE. Telecommunications Research Establishment (British).

Trigger pulse. A pulse which starts a cycle of operations.

Tuning. The process of adjusting circuits to resonance with the frequency of a desired signal.

UBS. Universal bomb sight.

UHF. Ultra-high frequency (200 to 3,000 mc).

V-beam. AN/CPS-6.

Vector (verb). To direct (an airplane) toward a moving target (military usage in aircraft interception).

Vector sight. A gunsight which gives the lead as a constant times the sine of the angle off. The constant depends upon the own speed of the aircraft, altitude, and ammunition.

VHF. Very high frequency (30 to 300 mc).

Video. Electrical form in which a returned radar echo is transmitted to the indicator to be made visible.

Visar. AN/APA-47.

V scope. See Figures 16 and 21, Chapter 20.

Vulture. AN/APG-13B.

Waveguide. A hollow pipe, usually of rectangular form, used as an r-f transmission line. The limits on the dimensions of the pipe are determined by the wavelength to be transmitted by the pipe, also by the shape of the pipe and the mode of transmission. There are other types of waveguides, such as solid dielectric cables, through which it is possible to transmit energy. Waveguides may be straight, twisted, curved, tapered, or flexible.

Window. Chaff. Radar countermeasure, consisting of strips of metal foil or metal-coated paper, cut to a calculated size, dropped from an airplane. A small quantity of the material will reflect as much energy as an aircraft.

Wind triangle. See Figure 8, Chapter 13.

X band. Refers to wavelengths around 3 cm.

Yagi antenna. See antenna, yagi.

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INDEX

The subject indexes of all STR volumes are combined in a master index printed in a separate volume. For access to the index volume consult the Army or Navy agency listed on the reverse of the half-title page.

A scope indicator, 31, 116, 284, 289
A1 gun sight, 257
Absorbing screens, radar, 29
Absorption bands, atmospheric, 55
Absorption cone for radar testing, 186
Acceleration integrator bomb release (AIBR), 145
Aerial combat, use of radar; *see* AGL radar, AGS radar, ARO radar
Aerial reconnaissance by beacon navigation, 126
Aerodynamic lead pursuit course, 248
AEW radar (airborne early warning), 33, 53, 300
AGL radar (airborne gun-laying), 198, 200–218
  accuracy, 212
  antenna, 204, 213
  anti-jamming considerations, 210
  automatic following, 201
  automatic frequency control, 210
  automatic gain control, 210, 215
  automatic range tracking, 209, 215
  boresighting, 200, 210
  computers, 201, 212
  defensive systems, 202, 217
  design factors, 204–212
  functions, 200
  IFF, 202, 210
  indicators, 210, 215
  jet-propelled aircraft, 205
  offensive systems, 202, 218
  operation, 200
  photographic tests, 212
  recommendations for future equipment, 212
  servomechanism, 207
  specifications, 202
  testing, 262–275
  wavelength, 204
AGL radar systems; AN/APG–1, 200–218
  AN/APG–2, 200–218
  AN/APG–3, 200–218
  AN/APG–16, 200–218
  AN/APG–19, 200, 202, 205, 206
  Black Maria, 212
  Sperry AGL–2, 206
AGS radar (airborne gun sight), 219–225, 248–261
  antenna, 220
  application, 219
  component packaging, 219
  computer, 220, 248–261
  identification, 223
  indicator, 219
  photographic tests, 266
  sights for fixed guns, 220
  stability, 222
  testing, 262–275
AGS radar systems; AGL–T, 222
  AN/APG–15, 224
AI radar (aircraft interception), 175–193
  angular coverage, 179
  antenna beamwidth, 178
  firing methods, 191
  frame speed, 179
  future trends, 175
  ground and sea clutter, 180, 192
  ground-controlled interception (GCI), 175, 176
  gun-laying, 177
  independent interception, 175, 176
  indicator display, 182
  infrared techniques, 176
  interception techniques, 188
  maintenance, 25, 185
  maximum range, 178
  navigational function, 180
  pre-radar AI techniques, 188
  probability of interception, 190–191
  radar contact probability, 189
  radome design, 186
  range clock, 192
  range performance, 178
  scans, 181, 186
  sensitivity, 178
  ship-controlled interception, 175
  special test equipment, 185
  tactics, 188–193
  windscreen projection, 187
AI radar systems for controlled interception; AIA, 184
  AN/APG–3, 183
  AN/APG–16, 183
  AN/APS–6, 183–188
  AN/APS–6A, 184–186
  AN/APS–19, 183–186
  SCR–540, 183
AI radar systems for independent interception; AN/APG–1, 183
  AN/APG–2, 183
  AN/APS–4, 184
  AN/APS–21, 183–186
  SCR–520, 183
  SCR–720, 183
Aided-tracking box for the "Vulture," 234
Air mass coordinate test method for bomber gunnery, 272
Air navigation; *see* Navigation, aerial
Air speed meter for GPI, 98
Air to ground combat, radar for, 252
Air to ground fire-control systems, tests of, 273
Airborne cannon, 256
Airborne Early Warning system (AEW), 32, 53, 300
Airborne fire control radar systems; *see* AGL radar, AGS radar, ARO radar
Airborne gunsights; *see* AGL radar, AGS radar, ARO radar
Airborne magnetometer, 11
Airborne moving target indication (AMTI), 176, 181, 279–302
  cancellation unit, 283–285
  doppler principle, 279
  limits of detectability, 284, 300, 302
  presentation methods, 283, 287, 290
  recommendations, 301
  theory, 279
Airborne moving target indicator systems; Butterfly (AN/APS–26), 284, 287
  Cadillac (AN/APS–20), 300–302
  Firefly (AN/APS–27), 290
Airborne radar mapping systems; *see* Radar mapping systems
Airborne radar ranging principles, 59
Airborne radar systems for bombing; *see* Radar bombing
Airborne range-only radar systems; *see* ARO radar systems
Aircraft interception, pre-radar techniques, 188
Aircraft interception, radar; *see* AI radar
Aircraft velocity vector, 37
Airspeed determination for GPI, 98
Altimeter, Kollsman aneroid, 146
Altitude circle on radar screen, 48
Amplifier, low input capacity, 295
Amplitude cancellation unit for AMTI, 293
AMTI; *see* Airborne moving target indicator
AN/APA–5 (LAB bombsight), 78, 290
AN/APA–5 range computer, 80
AN/APA–46 (Nosmo), 74–76
AN/APA–47 (Visar), 74–76
AN/APG–1 (AI and AGL system), 183, 191, 198–207, 210, 212, 261
AN/APG–2 (AI and AGL system), 183, 202–205, 261
AN/APG–3 (AGL system), 183, 202–206, 261
AN/APG–4 (Sniffer), 139
AN/APG–5 (ARO system), 226, 229, 262
AN/APG–13 (Falcon), 198, 199
AN/APG–13A (Falcon), 199, 226
AN/APG–13B (Vulture), 199, 218, 226, 256
AN/APG–15 (AGS system), 219, 220, 261
AN/APG–15B (AGS system), 223, 264
AN/APG–16 (AGL system), 183, 202–205, 207, 210
AN/APG–19 (AGL system), 202, 205, 207
AN/APG–21 (Terry), 199
AN/APG–22 (AGS system), 149

AN/APG-24 (AGS system), 149
AN/APN-1 (altimeter), 139
AN/APQ-5 (LAB), 78, 290
AN/APQ-7 (Eagle), 50, 58, 63, 67, 73
AN/APQ-10, Radar bombing computer, 66
AN/APQ-13 (H2X), 50, 59, 67
AN/APQ-13, Mod. II, (MX-344), 82
AN/APS-3 (low altitude radar bombing system), 58
AN/APS-4 (ASV and AI radar), 177
AN/APS-6 (AI system), 183, 191
AN/APS-6A (AI system,) 184
AN/APS-15 (H2X system), 16, 50, 54, 58, 64, 67, 71, 100
AN/APS-15A dial computer, 71
AN/APS-15A modulator, 287
AN/APS-15A range unit, 61
AN/APS-15BM radar system, 50
AN/APS-19 (AI system), 183–186
AN/APS-20 (Cadillac) radar system, 59, 300–302
AN/APS-21 (AI system), 183–186
AN/APS-26 (Butterfly), 287
AN/APS-27 (Firefly), 290
AN/APS-30-series ASV systems, 22
AN/APS-33 (ASV system), 30, 50, 58, 59
AN/APS-34 (ASV system), 50, 59
AN/APS-35 (ASV system), 50
AN/APX-15 (Ella), 224
AN/ARA-17 release point indicator, 159
AN/ASG-10 toss-bombing system, 153
Aneroid altimeter, 146
Angular-travel lead, 258
Antennas, radar; beamwidth, 178
  dipole arrays, 13, 28
  gyro control, 19
  hemispherical search, 216
  low-frequency ASV patterns, 13
  polystyrene rod type, 246
  radiation patterns, 52, 55
  rotating disk, 213, 220
  rotating paraboloid, 213, 220, 236
  search antenna, 213
  size and weight, 204
  small antennas, 246
  stabilization, 18, 19
  test equipment, 64
  tracking antenna, 213
  Yagi array, 13
Anti-jamming provisions, 118, 210
Anti-radar devices, 11, 118, 209, 210
Anti-submarine tactics with ASV, 32
AN/UPN-1 portable beacons, 114
Applied Mathematics Panel, NDRC, 197, 235, 249–263
Arma resolver, 90
ARO radar (airborne range-only), 226–247
  advantages, 226
  antenna recommendation, 246
  computers, 248–261
  future developments, 244–247
  Lighthouse Transmitter-Receiver unit (LHTR), 226
  tactical application, 226
  testing, 262–275
ARO radar systems; AN/APG-5, 148, 226, 229
  AN/APG-13A (Falcon), 226, 231
  AN/APG-13B (Vulture), 226, 234–241
  AN/APG-21 (Terry), 226, 234, 241
ASB radar (ASV system), 14
ASB-3 (ASV system), 58
A-scope indicator, 31, 116, 284, 289
ASE radar (ASV system), 13
ASV radar (air to surface vessel), 9–33
  antenna patterns, 2, 13
  antenna stabilization, 18, 19
  azimuth resolution, 17, 50
  beacon equipment, 22
  design, 17–24
  design criteria, 9
  identification of friend or foe, 33
  indicator, 13, 31
  limitations, 30, 33
  maintenance, 25–30
  manuals of instruction, 29
  maximum range, 30
  means of detection, 13–16
  methods of attack, 32
  military uses, 10–12
  navigational feature, 9, 22
  operator fatigue and safety, 22, 31
  panel layout of set, 21
  patrol methods, 31
  peacetime uses, 9
  performance, 25–35
  pulse duration, 17, 18
  recommendations, 32
  reliability, 21
  scanning rate, 20
  sea return, 20
  test equipment, 29
  Vixen attachment, 11
ASV radar systems; AN/APS-4, 177
  AN/APS-30, 20–24
  AN/APS-31, 23
  AN/APS-3B, 23, 30
  ASB radar, 14
  ASE radar, 13
  ASVC radar, 13
ASVC radar, (ASV system), 13
Attack methods with radar, 32
Audio frequency phase shifter, 283
Audio indication for radar system, 287
Automatic controls for radar systems, 58
Automatic following radar; *see* AGL radar
Automatic frequency control and operator comfort (radar), 58
Automatic frequency control with AGL radar, 206, 210
Automatic gun laying; *see* AGL radar
Automatic range tracking with AGL radar, 209
Azimuth control with MX-344 computer, 83
Azimuth errors, effect on GPI, 100
Azimuth resolution in ASV radar, 17, 50
B scope presentation, 15, 57, 77, 182, 210
B-29 pedestal sight, 251
B-29 standard computer, 258, 260
Ballistic calibration of radar for cannon fire, 252
Ballistic cams for Vulture, 235
Ballistic computation with MX-344 computer, 85
Bandwidth, optimum radar receiver, 56
"Barber Pole," skid indicator, 273
Battle of the Bulge, 279
Beacon bombing, 104–130
  advantages and disadvantages, 104, 127
  airborne beacons for extending range, 127
  beacon offset bombing, 105, 121
  GPI computer design, 130
  methods of increasing range, 127
  methods of simplifying operation, 129
  types of systems, 104
  Universal computer design, 130
Beacon bombing systems; beacon offset systems, 105, 121
  Gee, 39, 123, 124
  Gee-H, 108
  Micro-H, 109–113
  Oboe bombing, 116–118
  Rebecca-Eureka equipment, 113
  Shoran, 114–116
  SS Loran, 39, 124
Beacon navigation; aerial reconnaisance and mapping, 126
  paratroop dropping, 125
Beacon responders for AGS, 223
Beacon test equipment, 64
Beacons, general description, 9
Beamwidth of several typical radar systems, 50
Bell telephone laboratories, MX-344 computer, 82
Bias error of gun sights, 262
Black Maria (identification system), 212
"Blackout unit" for Gee-H, 108
Blimps using ASV radar, 11
Blind bombing with Gee, 106, 123
Blind bombing with SS Loran, 106, 124
Blind firing, 191
Bomb release circle, 67
Bomber, determining motion of, 272, 273
Bomber fire-control systems, tests of, 269
Bomber gunnery; air-mass coordinate test method, 272
  pre-radar, 248
  radar tracking, 251
  range-only radar, 250
Bombing, visual, 39, 42, 45
Bombing accuracy; methods of determining, 155
  use of h + b technique, 69
Bombing computers, radar; acceleration integrator, 145

  AN/APA-5 computer, 79
  AN/APQ-5 computer, 78
  for beacon bombing, 130
  for Eagle systems (AN/APQ-7), 67, 73
  for Gee-H bombing systems, 109
  for ground controlled bombing, 133
  for H-bombing systems, 108
  for MC-627 plotting table, 133
  for Nosmeagle, 74, 75
  for Nosmo (AN/APA-46), 74
  for Shoran, 114
  for toss bombing, 145
  for Visar (AN/APA-47), 74
  general discussion, 66
  Ground Position Indicator (GPI), 90, 130
  impact predicting computers, 67–72, 133
  LAB computers, 77, 79
  MX-344, 82–86
  non-synchronous, 66–72
  Norden bombsight, 72
  semi-synchronous, 66, 72–77
  synchronous, 66, 79–86, 133
  test equipment, 64
  Universal bombsight, 130
Bombing procedure; computation of release points, 40
  from fighter planes, 252
  from low altitudes, 226
  identification of target, 39
  navigation to target, 38, 39
  radar vs. visual methods, 45–46
  steering to release point, 41
Bombing scoring; aircraft camera methods, 155
  necessity, 5
  photography from ground, 156
  photo-reconnaissance, 165
  PPI photographs, 164
  use of ground radar systems, 157
Bombing systems, radar, 37–172
  beacon bombing, 104–130
  beacon offset, 121, 122
  Gee, 123, 124
  Gee-H, 108
  ground controlled, 131–138
  Ground Position Indicator, 87–103
  H-systems, 106–116
  hyperbolic navigation, 122–125
  maintenance, 63–65
  mapping systems, 47–59
  Micro-H, 109–113
  Norden bombsight, 42
  Oboe beacon bombing, 116–129
  procedure, 37
  ranging, 59–63
  Rebecca-Eureka, 113
  Shoran, 114–116
  testing, 155–166
  training personnel, 166–172
  toss bombing, 139–154
  visual bombing, 42, 45
Bombsights; *see also* Bombing computers, radar
  Norden, 42, 72, 73
  requirements, 45
  Universal bombsight (UBS), 66, 130

Boresighting; AGL radar, 200, 211
  AI radar, 186
British Gee navigation system, 106
British gyro gunsight Mk II-c, 221
British H2S radar system, 57, 67
B-scope presentation, 15, 57, 77, 182, 210
BUPS radar beacon, 121
BUPX radar beacon, 121
Butterfly (AN/APS-26); general description, 287–289
  performance, 290
  tactical uses, 287

C scope presentation, 182, 210
Cadillac system (AN/APS-20), 59, 300–302
Cameras for AGS system tests, 266, 272
Cameras for bomb scoring, 155, 165
Cancellation unit for AMTI, 283, 292
Cannon fire control, airborne, 252
"Carpet," 175
Circuits, electronic; amplifier, low input capacity, 295
  audio frequency phase shifter, 283
  detector balance bias (DBB) circuit, 181
  fast time constant (FTC) coupling circuit, 181
  instantaneous automatic gain control (IAGC) circuit, 181
  jitter circuit, 108
  local oscillator, stable (STALO), 283, 301
  phantastron delay circuit, 63
  phase detector, 208
  trigger circuit, 61
"Close-Support" bombing, 131
"Clutter," 104, 180, 284
COHO (CW oscillator), 282, 301
Communications in ground-controlled bombing, 136
Comparator for Shoran, 115
Computers, airborne gunsighting and gunlaying; *see* Gunsights
Computers, airborne rocket, 257
Computers, bombing; *see* Bombing computers, radar; Bombsights
Conical scan, 200–209, 213–215, 241, 246
Controls for radar systems, recommendations, 58
Corner reflector on life rafts, 11, 12
Cosecant-squared antenna pattern, 52, 55
Countermeasures, radar, 11, 118, 175, 209, 210
Course determination by GPI, 88, 94
Cross trail, 40
Crystal checker for radar crystals, 29
C-scope presentation, 182, 210
Cursor, electronic, 58

Dead reckoning, aerial, 37
Deflectometer method of testing bomber gunnery, 270, 271

Delay circuits, 61, 63, 69, 71
Delay line, mercury, 292
"Delayed" PPI, 57
Detector balanced bias (DBB) circuit, 181
Dial computer (AN/APS-15A), 71
Dipole antenna arrays, 13, 28
Direction finding stations, ground based, 38
Directional coupler (transmission line), 28
Director-type gun sights, 220, 258
Dispersion error of fire-control systems, 262
Displays, radar; *see* Radar displays
Distortions of radar maps, 47–54
Disturbed-reticle gun sight, 221, 258
Dome design for AI radar, 186
Doppler effect, use in radar bombing, 75, 279, 284
Draper-Davis (Army A-1) sight, 241, 246, 257, 260
Draper-Davis S-9 computing gunsight, 218
Drift angle, 40
Drum computer, (AN/APS-15), 67
Duplexer, 14, 206

"Eagle" radar system (AN/APQ-7)
  beamwidth, 50
  computer, 67, 73
  description, 59
  test calibrators, 63
Echo box (radar test equipment), 29, 289
Electronic cursor, 58
Enemy aircraft interception; *see* AI Radar
Eureka beacon, 113
Expanded gain, 215

Falcon (AN/APG-13), 199
Falcon (AN/APG-13A), 229, 252
Fast time constant (FTC) circuit, 181
Fighter aircraft; all purpose sights, 257
  gunnery radar, 251
  gunnery tests, 272
  pilot problems, 252
Fire control radar, airborne, 197–275; *see also* AGL radar, AGS radar, ARO radar
  air-to-ground systems, 252, 273
  computer problems, 248–261
  system types, 197, 270
Firefly (AN/APS-27); cancellation units, 292–295
  comparison with Butterfly, 290
  general description, 290
  performance, 300
  tactical uses, 290
Firing tests with AGL radar, 212
Fix computation with GPI, 87, 90
Fixed guns, computer use, 220
Flare dropping with Gee, 124
Fluorescent maps for radar bombing, 170
Foot-pedal ranging, 250

Frequency meter, 29
Frequency pulling of magnetron, 206, 210
FTC coupling circuit (Fast time constant), 181
Future range, 272

G scope presentation, 182, 225
Gain control, automatic, 181
Gain expander, 235
GCI (Ground controlled interception), 175, 188, 204; *see also* AI radar
GE pantograph scanner, 206
GE standard B-29 computer, 258, 260
GE standard B-29 pedestal sight, 251
Gee system; airborne instrumentation, 123
  blind bombing, 123
  comparison with H and Oboe bombing systems, 106
  flare-dropping pathfinder operations, 124
  ground station arrangement, 123
  limitations, 106, 124
Gee-H bombing system, 108–109
Gisholt scanner balancer machine, 186
GPI; *see* Ground Position Indicator
Ground based direction finding station, 38
Ground clutter, 284
Ground controlled bombing; communication, 136
  computer, 133
  plotting table (MC–627), 133
  radar system (SCR–584), 132
  theory, 131–132
  unified control system, 136
  vectoring, 136
Ground controlled interception (GCI), 175, 188, 204; *see also* AI radar
Ground Position Indicator, (GPI), 64, 87–103
  air speed meter, 98
  associated equipment, 96
  computer mechanism, 90
  errors, 96–99
  functions, 87
  geometry, 87–90
  operational techniques, 101–103
  radar requirements, 99–101
  recommendations, 103
  test equipment, 64
  use with beacon bombing systems, 130
Ground stations for Shoran, 114
Ground Track Aiming Point (GTAP), 131
Ground velocity vector, 37
GSAP camera (N4A), 266
G-scope presentation, 182, 225
Gun climb, 264
Gun roll errors, 258
Gunlaying, radar-automatic; *see* AGL radar
Gunnery firing rules, 248
Gunnery scoring, aerial; AGL photo-scoring, 212
  AGS tests, 266
  bomber gunnery, 270
  deflectometer method, 270, 271
  fighter gunnery, 272
  necessity, 5
  photometeoronic method, 272
  Texas sight-testing machine, 262
  Tri-camera methods, 262, 270
  W–2 fighter-sight assessor, 273
Gunsight testing, 262–275
Gunsights, airborne; *see also* AGL radar, AGS radar, ARO radar
  AI radar, 177
  all-purpose sight, 257
  Army K-14, K-15, and K-17, 221, 262
  B-29 pedestal sight, 251
  B-29 standard computer, 258, 260
  British gyro Gunsight Mk II-c, 221
  director-type, 220, 258
  disturbed recticle, 221, 258
  Draper-Davis A-1, 241, 246, 257, 260
  Draper-Davis S-9 computing sight, 218
  electrical integrator type, 258, 260
  Fairchild K-8, 258
  fixed guns, 220
  general discussion, 258
  gyro, 221, 258, 260, 262
  lead computing, 258
  Mark 18, 222, 251, 258, 260, 262
  Mark 21 and Mark 23, 222
  non-gyro, 258, 260
  optical ring, 258
  PUSS (Pilots Universal Sighting System), 241, 257
  rate sights, 250, 258
  Sperry K-4, 258, 260
  types, 258
  vector sights, 258
Gunsights, manually-directed with radar scope; *see* AGS radar
Gunsights, radar range-only; *see* ARO radar
Gyro controlled antennas, 19
Gyro gun sights, 221, 258
"Gyrosyn" compass, 98

H bombing systems; advantages and disadvantages, 104
  Gee-H, 108–109
  general characteristics, 106
  Micro-H, 109–113
  paratroop dropping application, 114
  Rebecca-Eureka, 113
  Shoran, 114–116
h + b technique for H2X bomb computers, 69
H2S radar system, British, 57, 67
H2X bombing, 164
H2X drum computer, 67
H2X radar systems; AN/APQ–13, 50, 58, 59, 67
  AN/APS–15, 16, 50, 58, 64, 67, 71, 100
  AN/APS–15A, 71
Harmonization of scanner, 186
Hit probability nomogram for gun fire, 262
"Holy Moses"; *see* Rockets
Homing operations, 10, 11
HVAR (High velocity aircraft rockets), 254
Hyperbolic navigation systems; advantages and disadvantages, 106, 122
  comparison of SS Loran and Gee, 124

Identification as friend or foe, (IFF);
  AGL radar, 202, 212
  AGS radar, 212, 223
  AI radar, 175, 178
  ASV radar, 33
  Black Maria, 212
  propeller modulation, 223
  use of GPI, 102
Impact-predicting bombing computers; dial computer, 71
  H2X drum computer, 67
  inadequacies of, 72
  modified H2X drum computer, 70
Independent interception, 175, 176; *see also* AI radar
Indicators, radar; *see* Radar displays
Infrared techniques for AI radar, 176
Instantaneous automatic gain control (IAGC) circuit, 181
Instrument navigation, 38, 39; *see also* Navigation, aerial
Interception of enemy aircraft; *see* AI radar
Interference spots on PPI, 22

Jamming, countermeasures against, 119, 210
Jet-propelled aircraft, difficulty of radar detection, 205
Jitter circuit for Gee-H bombing system, 108

K–4 sight, Sperry, 258, 260
K–8 sight, Fairchild, 258
K–15 gyro sight, 262
K-band radar systems; AN/APS–34, 59
  description, 59
  limitations, 17
  rapid scan, 50, 59
  use for AGL, 205
Kollsman aneroid altimeter, 146

L Scope indicator, 183
LAB computers, 77
Lead angle, 248
Lead computing gunsights, 258
Lead problem in aerial combat, 248
Lead pursuit course, 248
Lighthouse transmitter-receiver (LHTR) unit, 219, 226, 236
"Lobe-switching," 14
Local oscillator, stable, ("STALO"), 283, 301
Long wave ASV radar, 13
Long wave beacons, 14
Long wave radar for AI, 188
Long wave systems for beacon offset bombing, 121
Loran, 32, 39
Low altitude bombing computers, 77

M scope indicator, 233, 252
Magnetic airborne detector, 11
Mail transference guided by ASV radar, 9
Maintenance, radar; airborne bombing system, 63–65
  ASV radar, 25–30
  fire control equipment, 264
  instruction manuals, 29
  personnel, 29, 167
Manually-directed radar gunsights, 219–225; *see also* AGS radar
Mapping, radar; *see* Radar mapping, Radar mapping systems
Maps for radar use, fluorescent, 170
Mark 18 gyro sight, 258, 262
MC–627 plotting table, 133
Mercury delay lines, 292–295
MEW (Microwave Early Warning radar), 137
Micro-H bombing systems; accuracy, 166
  Mark I, 109–111
  Mark II, 111–112
  Mark III, 112, 113
Moving target indicator; *see* Airborne moving target indicator
MX–344 bombing computer, 82–86

Navigation with radar, aerial; AI radar, 180
  ASV radar, 9
  Gee, 123, 124
  general discussion, 37
  GPI, 101
  hyperbolic systems, 106, 122–124
  SS Loran, 124
NDRC Division 7, 197
Night fighting techniques; AGL radar, 210
  AI radar, 175
Noise figure in the radar receiver, 27, 56
Non-synchronous bombing computers; dial computer, 71
  H2X drum computer, 67
  h + b technique, 69
  impact predicting computers, 67
  modified H2X drum computers, 70
Norden bombsight, 42, 72, 73, 82
Norden synchronous computer, 66, 77, 82
Nosmeagle bombing system, 75
Nosmo (AN/APA–46) bombing computer, 74–77, 289

Oboe beacon bombing systems; advantages and disadvantages, 105
  Mark I, 116–118, 129
  Mark II, 118, 119
  Mark III, 120
Offset bombing, 40, 66, 89, 90, 121
Operator, radar; *see* Radar operator
Optical methods for bomb scoring, 155
Optical range determination, errors, 267
Optical ring gun sights, 258
Optical-plus-radar fire control; *see* ARO radar, Gunsights
"Own-speed lead" formula, 248
Own-speed sight, 248, 258

Palmer scan, 202, 207
Panel layout of ASV radar set, 21
Pantograph scanner, 206
Parallax, effect on rocket sighting, 254
Paratroop-dropping guided by radar, 114
Paratroop-dropping with aid of beacon navigation, 125
Patrol with ASV radar, 10, 31
Phantastron delay circuit, 63
Phase detector, 208
Photographic scoring for aerial bombing, 155, 165
Photographic scoring for aerial gunnery, 212, 262
Photo reconnaissance for testing bombing accuracy, 165
Photo reconnaissance with Shoran, 126, 127
Photo-theodolite method of bomb scoring, 156
Pilot's direction indicator (PDI), 84
Plan position indicator (PPI); bomb release point, 67, 74
  distortion, 49, 72
  three-tone PPI presentation, 57
  use as a map, 47
  use with Micro-H Mark I, 110, 111
  use with Microwave ASV radar, 15
Plotting tables for bomb scoring; MC–627, 157
  RC–294, 157
  RC–305, 164
Polarization of radar beams, 20
Polyrod antenna, 246
Position determination of aircraft by GPI, 87
Power absorption cone for AI radar 186
PPI; *see* Plan Position Indicator (PPI)
Pulse duration in ASV radar, 17
Pursuit course rules, 248
PUSS (Pilots universal sighting system), 241, 257

Radar beacons; *see* Beacons
Radar bombing; *see* Bombing systems, radar
Radar bombing computers; *see* Bombing computers, radar
Radar boresights, 186, 200, 211
Radar contact probability, 189
Radar development agencies, coordination, 259–261
Radar displays; *see also* Radar mapping
  A–scope, 31, 116
  B–scope, 15, 57, 77, 182, 210
  British H2S Mark IVa display, 57
  C–scope, 182, 210, 212
  delayed PPI, 57
  fixed terrain airborne display, 57
  G–scope, 182
  L–scope, 183
  M–scope, 233, 252
  PPI, 15, 47, 67, 72, 74, 110
  V–scope, 234, 236
Radar equipment testing; *see* Testing, radar equipment
Radar for air-to-ground combat, 252
Radar for bomber gunnery, 250
Radar for cannon fire, 252
Radar for fighter gunnery, 251
Radar for rocketry, 260
Radar for toss bombing, 148
Radar gunsights; *see* Gunsights
Radar maintenance; *see* Maintenance, radar
Radar mapping, 39, 47–59, 66–86
  computers, 66–86
  distortion due to airplane motion, 53
  distortion due to antenna pattern, 52
  maximum range, 54
  point of departure, 38, 39
  PPI spot size limitations, 49
  presentation other than PPI, 57
  recommendations for improvement, 58
  resolution, 49–52
  slant range distortion, 47
Radar mapping systems; AN/APQ–7 (Eagle), 50, 58, 63, 66, 73
  AN/APQ–13, 50, 58
  AN/APS–3, 58
  AN/APS–15, 50, 54, 58
  AN/APS–20 (Cadillac), 58
  AN/APS–33, 50, 58
  AN/APS–34, 50, 58
  ASB–3, 58
  rapid scan, 50, 58
Radar operator; comfort in ASV designs, 22
  cooperation with bombardier, 73
  cooperation with pilot (Falcon system), 231–233
  training, 166–172
Radar systems for airborne detection of surface vessels; *see* ASV radar
Radar systems for aircraft interception; *see* AI radar
Radar systems for bombing; *see* Radar bombing
Radar systems for fire control; *see* AGL radar, AGS radar, ARO radar
Radar systems for moving vehicle detection; *see* AMTI
Radar tracking, 202, 251
Radar training equipment, 169
Radar-optical fire control; *see* ARO radar, Gunsights
Radome design for AI, 186
Range, airborne radar; accuracy, 100
  advantages of radar ranging, 250
  AI radar, 178
  AN/APS–26, 287
  ASV radar, 25, 30
  calibration for bombing purposes, 61
  comparison with stadiametric ranging, 250
  delay circuits, 61
  errors, 61, 69, 267

  factors affecting, 54
  for rocket firing, 256
  h + b technique, 69
  maximum range, 30, 54–57
  measurements, 59
  range marks, 58, 59, 61
  resolution, 51
  stabilization, 19
  unit AN/APS–15A, 61
  unit test set, 63
Range clock for aircraft interception, 192
Range-only radar systems; *see* ARO radar
Rapid scan radar, 50, 53, 59
Rate computation, aircraft
  with GPI, 88, 91
  with Nosmo, 76
Rate gun sights, 258
Rate sights with stadiametric ranging, 250
RC–294 plotting device; errors, 163
  use in bomb scoring, 157
RC–305 manual plotting system for bomb scoring, 164
Rebecca-Eureka beacon homing equipment, 113, 122, 125
Receiver noise, radar, 56
Receiver performance figure, 25
Recommendations for future research; AGL radar equipment, 212
  airborne fire control radar systems, 198, 199, 244
  airborne radar mapping systems, 58
  ASV radar, 32
  beacon bombing improvement, 127
  GPI techniques, 103
  gunlaying with AI radar, 177
  MX–344 computer, 86
  radar system controls, 58
Recommendations for radar personnel training, 172
Release point computers, 40, 89, 96
Release point indicator AN/ARA–17, 159
Rescues at sea guided by ASV radar, 9
Resolving power, radar, 15, 50, 99
R-f test load, 29
Rockets; High Velocity Aircraft Rockets (HVAR), 254
  Holy Moses (5″ HVAR), 256
  radar ranging, 256
  sight setting, 253
  skid effect, 273
  Terry installation, 241
  Tiny Tims, 254
  trajectory drop, 255, 257
  Vulture installation, 235
Roll-stabilization of antennas, 19

Scanning; AGL radar, 205–207
  AI radar, 178, 181, 186
  ASV radar, 20
  conical scan, 200–209, 213–215, 241, 246
  criteria, 16
  Gisholt balancer, 186
  harmonization, 186
  helical, 185
  Palmer scan, 202, 207
  Pantograph scanner, 206
  rapid television scan, 214
  scanner balancer, 186
  Sperry AGL–2 system, 206
  spiral, 213
  very rapid, 53, 59
  wig-wag, 185
Schnorkel, 11, 32
Schools for training radar operators, 166
Scientists in warfare, use of civilians, 1–5
Scoring, aerial bombing; *see* Bombing scoring
Scoring, aerial gunnery; *see* Gunnery scoring, aerial
SCR–520 radar, 183
SCR–540 radar, 183
SCR–584/M radar, 132, 157, 287
SCR–720 radar, 183, 184
Sea clutter, 9, 20, 104, 180, 300
Sealed assemblies for radar systems, 24
Search with AGL radar, 202, 207
Search with ASV radar, 10
Secrecy and wartime research, 2
Semi-synchronous bombing computers, 66, 72–79
Sensitivity time control (STC) circuit, 181
Ship controlled interception (SCI), 175; *see also* AI radar
Shipborne night fighters, use of AGS, 219
Shoran; airborne installations, 114
  advantages and disadvantages, 116
  comparator, 115
  computer, 64, 115
  ground stations, 114
  indicator unit, 115
  mapping procedure, 127
  photo-reconnaissance recorder, 126, 127
  receiver, 116
  repeater schemes, 129
  test equipment, 64, 65
  transmitter, 115
  use of, 116, 126
Sight assessing machine (University of Texas), 271
Signal generator test set, 29, 64
Skid indicator, "Barber Pole," 273
Sky-wave synchronized Loran; *see* SS Loran
Slant range distortion, 47
Slant range velocity, 78
"Sniffer" equipment (AN/APG–4), 139
Sono-buoys, 32
Space modulation, 117
Spectrum analyzer, microwave, 29
Sperry AGL–2 scanning system, 206
Sperry K–4 sight, 258, 260
SS Loran; airborne instrumentation, 125
  blind bombing, 125
  comparison with H and Oboe bombing systems, 106
  navigational use, 124
Stabilization of airborne radar antennas, 19
Stable local oscillator ("STALO"), 283, 301
Stadiametric ranging, 250
Standing wave meter, 29
Storage tube, 286
Streamlined aircraft, difficulty of radar detection, 205
Submarine detection with ASV radar, 10, 11
Submarine escape tactics, 32
Surface clutter, 181
Synchronous bombing computers; AN/APA–5 (LAB Mk II), 78–82
  AN/APQ–5, 78
  AN/APQ–10, 66
  AN/APQ–13 (MX 344), 82–86
  GPI, 64, 87–103
  Norden synchronous computer, 66, 79
  UBS (Universal bombsight), 66

Tactics with radar systems; AGL radar, 200
  AGS radar, 219
  AI radar, 188–193
  AMTI, 279–302
  ARO radar, 226
  ASV radar, 10, 31
  beacon bombing system, 104
  beacon navigation, non-bombing, 125
  beacon offset bombing, 122
  ground controlled bombing, 131
  toss bombing, 139, 140
Tangential test signal, 25
Target Discrimination, (TD), 24
Target identification in bombing from aircraft, 38
Temporal cancellation unit for AMTI, 293
Terry (AN/APG–21), 149, 234, 241, 257
Testing, radar equipment; AGL radar, 212
  AGS radar, 262–275
  AI radar, 185
  beacon bombing, 64
  bombing computers, 64
  Butterfly, 289
  Eagle, 63
  GPI, 65
  radar maintenance, 29, 63
  range calibration, 63
  Shoran, 64
  test points on circuits, 27, 28
  toss bombing, 151
Texas sight-testing machine, 262, 271
Three tone PPI presentation, 57
Time-of-flight calibration of gunsights, 259
Tiny Tims, 254
Toss bombing; acceleration integrators, 145
  barometric element, 146
  description, 139

  from fighter planes, 252
  mathematical analysis, 140
  non-radar methods used, 145, 151
  tactics, 139, 140
  test results, 151
  use of radar, 139, 148, 153
Tracking radar, 202, 251
Trail of bomb, 40
Training equipment, radar, 169
Training of radar personnel, 166–172
Trajectory drop of rockets, 255, 257
Transmit-receive (TR) box, 206
Tri-camera method for testing flexible gunnery, 262, 270, 271
Trigger circuits, 61
Universal bombsight (UBS), 66, 130
University of Texas sight assessing machine, 271

V scope presentation, 234, 236
Vector gun sights, 248, 258
Victorville radar training experiment, 170
Video stretching, 24
Visar bomb computer, 66, 74
Visual bombing, 39, 42, 45
Vixen attachment for ASV radars, 11
Vulture system (AN/APG–13B); aided tracking, 234, 240
  arrangement and operation, 235–240
  ballistic cams, 235
  function, 234, 235
  LHTR, 236
  performance, 235
  range accuracy, 237
  rocket computer, 257
  use with cannon, 253

W–2 fighter-sight assessor, 273
Wig-wag scanner, 185
Wind velocity vector, 37, 38
"Window" (chaff), 175, 192
Windscreen projection in AI radar, 187

Yagi antenna system, 13

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